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Summary of Progress *of the* GEOLOGICAL SURVEY OF GREAT BRITAIN *and the* Museum of Practical Geology for the Year 1935

PART II

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of the

Geological Survey of Great Britain

and the

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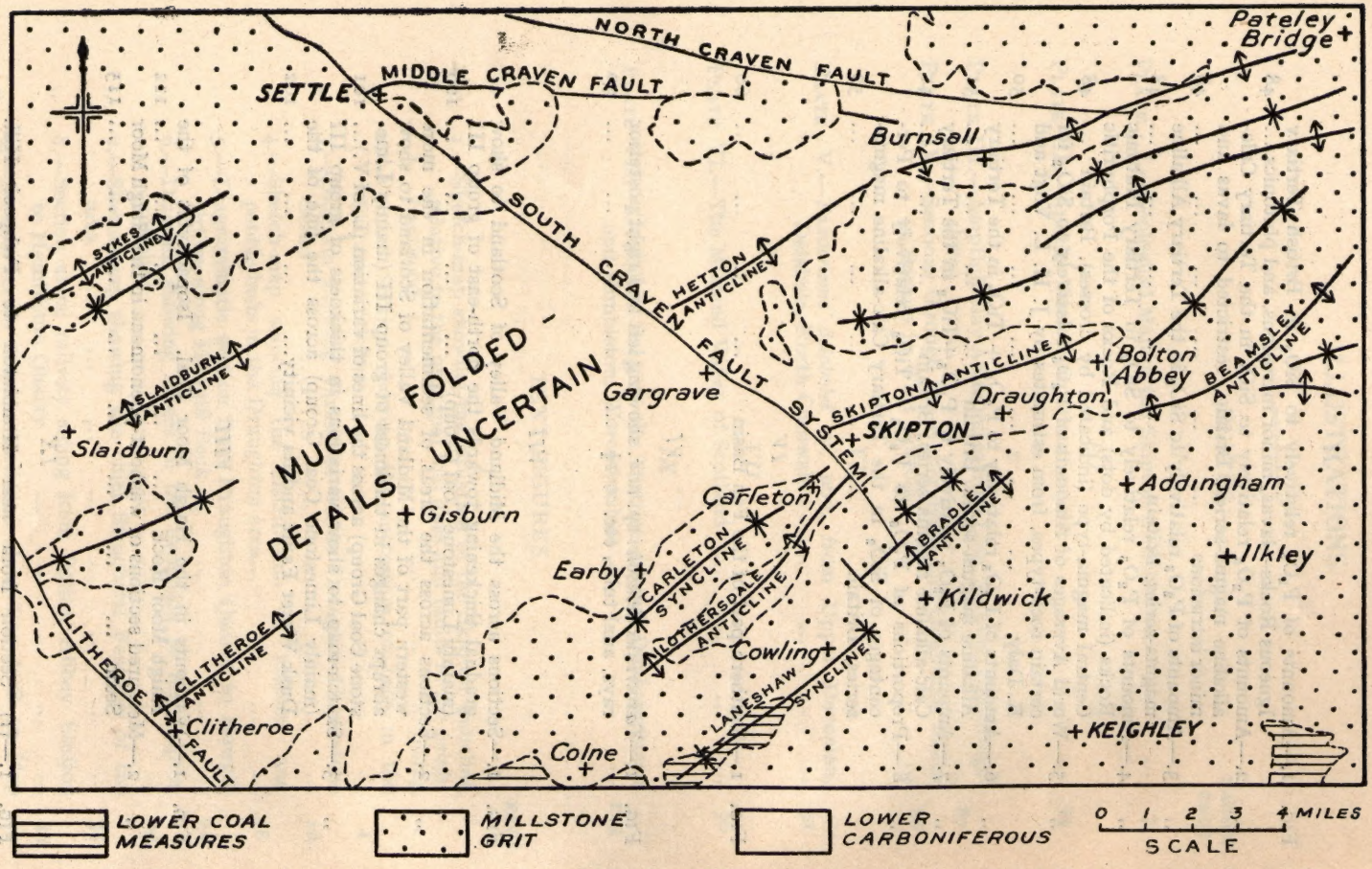

FIG. 1.—*Sketch-map showing the situation of the Skipton anticline relative to the principal fold axes and faults in the neighbourhood.*

I.—THE CARBONIFEROUS GEOLOGY OF THE SKIPTON ANTICLINE

BY

R. G. S. HUDSON, D.Sc., AND G. H. MITCHELL, M.Sc., PH.D., D.I.C.

Plate I. Text-figures 1—9.

INTRODUCTION

FOLDED rocks of Carboniferous age occupy the country from the North Craven Fault approximately as far southwards as a line joining Burnley and Harrogate. The individual anticlines and synclines, with axes trending generally in an east-north-easterly direction, are arranged *en échelon* and in no case do they seem to persist for more than a few miles. One of the most important of these folds is the Skipton anticline which extends from the Aire valley at Skipton to the neighbourhood of Bolton Abbey. (Fig. 1).

The effect of denudation on this structure has been to expose a large area of limestones and shales of Lower Carboniferous age. These rocks form, between the Aire and the Wharfe, a belt of country of comparatively low relief. Out of the midst of this ground the sharp ridge of Haw Bank abruptly arises. To the north, east and south, a bounding escarpment formed of the lowest grits of the Millstone Grit Series rises to a height of more than 1,000 ft. In places considerable deposits of drift mask the underlying solid rocks.

The area is included in the Carboniferous Central Province[1] and might be considered a standard succession for that basin of sedimentation since the greater part of the Dinantian is exposed and is, almost throughout, of mid-basin lithological facies and faunal phase. Moreover the age of the two major earth-movements which almost everywhere affected the Dinantian succession of the Central Province can be clearly demonstrated.

About four-fifths of the area described were surveyed by one of the authors (G.H.M.) during the resurvey by the Geological Survey. To complete the mapping of the structural unit, the remainder was mapped privately by him. The other author (R.G.S.H.) has also independently mapped a large part of the area and is responsible for the stratigraphical palaeontology. Both authors have been over the ground together and collaborated as to the interpretation of the structures. The authors are grateful for the ready help which they have received from Dr. C. J. Stubblefield, who has identified the fossils collected by the Survey with the exception of the corals, and to Mr. W. S.

[1] The Central Province is that basin of Carboniferous sedimentation between the Isle of Man—Lake District—North Pennine massif and the St. Georges Land—Mercian Highlands massif. The Harrogate, Skipton, Craven Lowland, Pendle, Bowland and Burnley areas may be grouped as the North-Central Province.

Bisat who has named all the goniatites. The assistance rendered by Mr. W. Dewar in making the official collections is warmly acknowledged.

History of Previous Research

Though there are many references in geological literature to the various excellent exposures of folded rocks in this area, no detailed or even general account of the geology has been published. Previous work may be grouped as follows:—

General outline:—Phillips (1836) following earlier authors, briefly referred to the anticlinal structure of the district and included it in his system of Ribblesdale folds which were further discussed by Hull (1868).

Lithological succession and correlation:—The 1 in. Geological Survey Map, Sheet 92 NE, was issued in 1889 but the memoir was not published. The south-western part of the area, however, is shown on Geological Survey Map, Sheet 92 SE, published in 1878, and was described in the memoir issued the following year. Papers by Dalton (1872) and Dakyns (1877) show that the succession of Haw Bank, Embsay and Eastby Limestones was recognized in the north of the area, but that correlation was not made with the folded area to the south. This was partially remedied by Tiddeman (1890) who recognized the equivalence of the Draughton and Eastby Limestones. He also made the first correlation with the Pendle succession, equating the Eastby Limestone with the Pendleside Limestone and the Haw Bank Limestone with the Chatburn Limestones.

Palaeontological succession and correlation.—No faunas have been previously recorded from this area. One of us (R.G.S.H., 1926), recognized the Tournaisian age of the Haw Bank Limestone and briefly stated the succession in terms of the coral-brachiopod zones. The correlation with the Pendle succession was completed by the correlation of the Embsay Limestone with the upper part of the Clitheroe Limestone.

Sedimentation and Structure.—Tiddeman (1890) initiated the study of the sedimentation by the recognition of the breccia in the Draughton Limestone. He considered the breccia to be of sedimentary origin, traceable north and passing into reef limestones [of the Craven Reef Belt] from which it was mostly derived, though Marr (1899) discussing in some detail the structure of the breccia, considered it to be of tectonic origin. Hudson (1933) briefly considered the position of the Skipton succession in the Craven sedimentation basin, while recent papers by Hudson (1933), Hudson and Versey (1935), and a note in the *Summary of Progress of the Geological Survey* (1935) mention some of the structural features of the area.

General Stratigraphical Succession

The greater part of the succession is one of mudstones, shales and dark-grey argillaceous limestones in varying proportion. (*See* Fig. 2). At three levels limestone is more abundant than shale. These limestone beds are distinguished as the Haw Bank Limestone, the Embsay Limestone and the Draughton Limestone[1] and the beds between the two former as the Halton Shales-with-Limestones and between the two latter as the Skibeden Shales-with-Limestones.[2]

Above the Draughton Limestone and Shales, a series of mudstones and shales with thin limestones is gradually replaced by shales with limestone bullions. These pass into ferruginous and micaceous shales, becoming more sandy upwards and are finally succeeded by the coarse sandstones and pebbly grits of the Millstone Grit. This shale series is the equivalent of the Bowland Shales of Phillips (1836), and that name is therefore used. The lithological succession is fairly constant throughout the area but there are great variations in thickness, especially in the Skibeden and Halton Shales-with-Limestones. The maximum thickness of the succession below the Skipton Moor Grit approaches 5,000 feet.

Identifiable fossils are rare, though at certain levels the limestones are composed of fossil fragments. In general the fauna is of the " modified limestone phase "[3] as in the Haw Bank and Embsay Limestones, or of " Zaphrentid phase " as in the shales both at the top of the Haw Bank and Embsay Limestones, at the base of the Halton Shales-with-Limestones and in the upper Draughton Limestone. A " normal shale fauna " only occurs towards the top of the Halton Shales-with-Limestones, while the Bowland Shales are almost throughout of " goniatite-lamellibranch phase." Bryozoan, ostracod and algal limestones occur and the Skibeden Shales-with-Limestones are of the dolomitic lagoon type, containing a fauna of spirorbid annelids, ostracods, trilobites and small gastropods and lamellibranchs. No " standard coral-brachiopod " or reef phase occurs. Nowhere does the fauna indicate anything but shallow-water conditions.

---

[1] A limestone at this horizon was mapped on the 1" Geological Survey Map, Sheet 92 NE, 1889, and later referred to in various papers as the Eastby Limestone (Dakyns, 1891; Hudson, 1926; Geological Survey, 1935). The use of this limestone as a stratigraphical division has been abandoned since its base is not capable of either lithological or palaeontological definition. The top of the Eastby Limestone is approximately that of the Draughton Limestone. The line taken as its base on the 1" Geol. Map is now mapped as at various levels in the upper part of the Skibeden Shales-with-Limestones.

[2] In the area to the west, the Carboniferous Limestone is exposed throughout the Craven Lowlands and there the succession below the Bowland Shales was first described by Tiddeman as:

Pendleside Limestone
Shales-with-Limestone
Clitheroe Limestone

These names have not been used in the Skipton area since their exact horizon at Clitheroe, the type area, is not known and therefore precise correlation is not possible. A preliminary correlation is Pendleside Limestone = Draughton Limestone; Shales-with-Limestone = Skibeden Shales-with-Limestones; Clitheroe Limestone = Embsay Limestone, Halton Shales-with-Limestones, and Haw Bank Limestone.

[3] These various types of shale and limestone faunal phase have been briefly discussed by Dixon (1911), Hudson (1924), and Reynolds (1926).

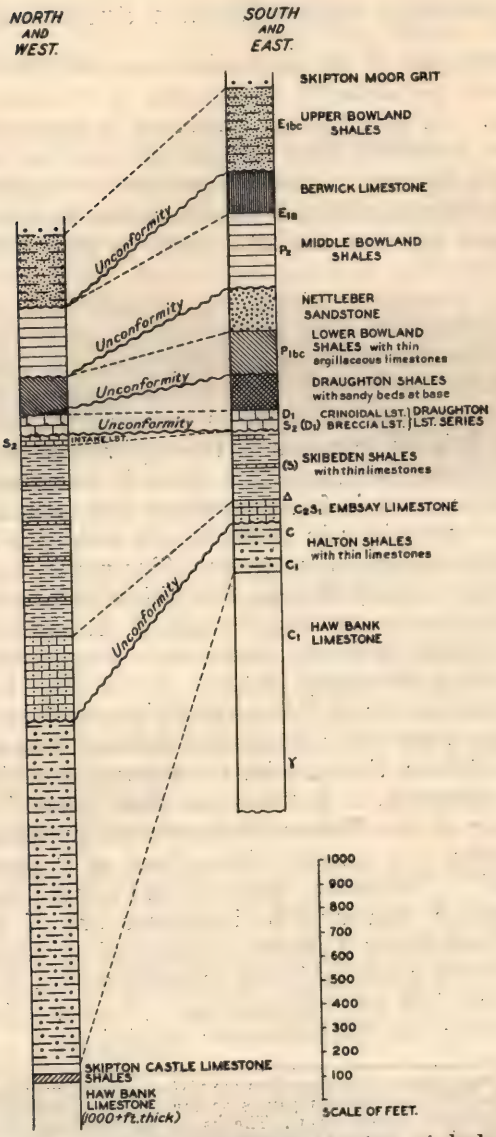

FIG 2.—*Vertical Section showing the succession of beds in the Skipton anticline.*

A sufficient fauna has been obtained to allow of an exact determination of the age of most of the beds. The goniatite-lamellibranch fauna of the Bowland Shales allows the reference of these beds to the zones of *Goniatites crenistria*, s.l. (P_1), *G. spiralis*, s.l. (P_2) and *Eumorphoceras pseudobilingue* (E_1) and has enabled these zones to be mapped. The goniatite collections have both confirmed the subdivision of these zones and also the recognition of faunal bands characterized by particular species of goniatites.

The succession of these bands has been noted but they have not been mapped. Detailed collecting would enable the position of several of these bands to be fixed and might reveal further lateral variations in the stratigraphical sequence. No goniatites of zonal importance have been recognized below the Bowland Shales and no correlation is therefore possible with the Beyrichoceras Zone.

The rest of the succession has been divided, mainly by means of the corals, into zones based on the coral-brachiopod zones of Vaughan. This succession is divided into three major zonal groups, γ-C_1, C_2-S_1, S_2-D_1. Faunal bands occur, rendered distinct by particular lithology, but lack of exposures prevents their being mapped in detail. The generalized succession is as follows :—

Skipton Moor Grits, E_1. 1,600 ft. thick.

Alternating beds of grit and shale, each group averaging less than 100 ft. thick. Grits usually coarse in grade, and in some beds gravelly, with quartz, quartzite and felspar gravel. No marine fossils. (Immediately above the Skipton Moor Grits there is a shale with a goniatite-lamellibranch fauna containing *Eumorphoceras bisulcatum* Girty. This horizon is known as the Edge Marine Band and is taken as the base of E_2).

Upper Bowland Shales, E_1. 350 ft. thick.

Dark silty shales, often ferruginous and micaceous, with striped siltstones and concretions of impure ironstone, often septarian. Goniatites and lamellibranchs occur in calcareous shale or in limestone bullion bands. Fish remains are found in other bands, and plant remains are common in goniatite-lamellibranch bands.
Characteristic fossils: *Cravenoceras malhamense, Eumorphoceras pseudobilingue* and *Posidonia membranacea.*

Berwick Limestone, E_1. 0-200 ft. thick.

Shales and impure black siliceous limestones. The latter contain much light-coloured crinoid debris with occasional shell fragments. When weathered, this bed forms a brown decalcified rock with crinoid stem-casts. Characteristic fossils: *Densiphyllum sp., Productus* cf. *concinnus, P.* (*Eomarginifera*) cf. *setosus, Cravenoceras leion, Eumorphoceras* cf. *pseudobilingue* [early form], *Posidonia* cf. *membranacea.*

Middle Bowland Shales, P_2. 300 ft. thick.

Dark shales, often ferruginous, and thin black impure limestones. A constant limestone bed occurs near the top of the series. Goniatite-lamellibranch fauna occurs almost throughout.
Characteristic fossils: *Goniatites granosus, G. newsomi, G. subcircularis, Posidonia* cf. *membranacea.*

Nettleber Sandstone (P_1). 0-175 ft. thick.

Compact, hard, fine-grained micaceous sandstone, with occasional carbonaceous traces. Strongly jointed. No fossils.

Lower Bowland Shales, P_{1b} and P_{1c}. 200 ft. thick.

Dark shales with many impure black limestones. Towards the base the beds are sandy and flaggy. Goniatite-lamellibranch fauna throughout. Characteristic fossils: *Posidonia becheri, Pterinopecten mosensis, Goniatites falcatus, G. sphaerico-striatus.*

Draughton Shales (P_{1a}?). 150 ft. thick.

Black calcareous shales with goniatites passing down into impure laminated and crinoidal limestones with bryozoa, and sandy shales. Phosphatic nodules in shales. Near the base a thin pebble bed, while flaggy sandstones form the lowest beds. No identifiable fossils.

Upper Draughton Limestone; Emmonsia beds, D_1. Up to 50 ft. thick.

Dark fragmental limestones with shale partings. These limestones mainly consist of bryozoan and shell debris often silicified and include numerous limestone pebbles. Dark grey limestones form the lower part. They are occasionally oolitic and contain goniatites and towards the base fragmental brachiopods. Probably small non-sequences and transgressions throughout the series.

Characteristic fossils: *Dibunophyllum* θ and ϕ [early forms], *Emmonsia parasitica, Michelinia* cf. *tenuisepta, Productus* (*Echinoconchus*) *elegans, P.* (*Overtonia*) *fimbriatus, P.* (*Krotovia*) *spinulosus, Parallelodon bistriatus* and *Goniatites sp.*

Lower Draughton Limestone; Breccia beds, S_2-D_1. Up to 50 ft. thick.

Compact light grey limestones in beds up to 3 ft. thick, mainly fragmental limestone and fossil debris with two coarse limestone breccia-conglomerates, thin shales and chert layers. Numerous small transgressions throughout the series. Fossils rare except above upper breccia-conglomerate. Most fossils in lower breccia-conglomerate derived.

Characteristic fossils: In lower beds *Cyathaxonia rushiana, Koninckophyllum* cf. θ [early form], Lithostrotions belonging to the *martini-sociale, minus-arachnoideum* and *affine-phillipsi* groups, and *Palaeosmilia murchisoni.* In upper beds *Chonetes* (*Plicochonetes*) *crassistrius* var. *minima, Productus* (*Krotovia*) *aculeatus, P.* (*K.*) *spinulosus, P.* (*Echinoconchus*) *elegans, P.* (*Avonia*) *youngianus* and *P.* (*Overtonia*) *fimbriatus.*

Skibeden Shales-with-Limestones, C_2-S_1, S_2. 350 ft.—1,500 ft. thick.

Dark calcareous mudstones and shales with compact fine-grained dark grey dolomitic and argillaceous limestones. Limestones often show brown dolomitic streaks and both carbonaceous and green chloritic flecks and clay pellets. Strings and nodules of chert in upper beds. Limestones weather light grey. Upper beds mostly limestone with little mudstone and known as Intake Limestone, S_2 (up to 70 ft. thick). Fossils rare except in Intake Limestone and at base.

Characteristic fossils: *Palaeosmilia sp.* of *P. multilamellatum*-group and early Clisiophyllids at base (C_2-S_1); *Caninia amplexoides, Cyathaxonia rushiana, Hettonia, Michelinia tenuisepta, Zaphrentis derbiensis, Chonetes* (small vars.) near top of series (Intake Lmst., S_2).

Embsay Limestone, C_2 and C_2-S_1. 60 ft.—350 ft. thick.

Well-bedded compact fragmental limestones often richly crinoidal, bryozoan and with ostracods. Also laminated fine-grained and thin flaggy compact limestones with shale partings which increase towards the top of the series. Chert-strings and nodules are found throughout. Oolites and contemporaneous breccias with oolitic matrix occur in lower part. Marked limestone conglomerate near base in eastern outcrops.

Characteristic fossils: *Cyathaxonia cornu,* early Clisiophyllids, *Palaeosmilia* (early forms), *Rhopalolasma, Zaphrentis densa, Composita ambigua, Daviesiella* cf. *comoides, Punctospirifer.*

Halton Shales-with-Limestones. C_1. 50 ft.—1,600 ft. thick.

Dark calcareous shales and mudstones with thin dark compact argillaceous, and in some cases, dolomitic limestones. " Zaphrentid phase " fauna at base, " normal shale " fauna near top. Occasional

GEOLOGICAL MAP OF THE SKIPTON ANTICLINE

SCALE

0 ¼ ½ MILE

INDEX

- SKIPTON MOOR GRIT
- UPPER BOWLAND SHALES
- *Unconformity*
- BERWICK LIMESTONE
- MIDDLE BOWLAND SHALES
- *Unconformity*
- NETTLEBER SANDSTONE
- LOWER BOWLAND SHALES
- *Major Unconformity*
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- HALTON SHALES (WITH THIN LIMESTONES)
- SKIPTON CASTLE LIMESTONE
- SHALE
- HAW BANK LIMESTONE

E₁ P₂ P₁ D S C2Sl C C1 — NAMURIAN, VISEAN, TOURNAISIAN

60/ DIP OF STRATA. THE ANGLE IN DEGREES

\+ HORIZONTAL STRATA

— VERTICAL STRATA

↕ ANTICLINE

FAULTS: CROSS-MARK ON DOWNTHROW SIDE.

⊙50 FOSSIL LOCALITY

A——B. LINE OF HORIZONTAL SECTION (SEE TEXT-FIG.)

✳ SYNCLINE

(2621) 8888, 910, 4/37. GP3213 & R LTD

small crinoid, shell and trilobite debris throughout. Characteristic fossils: *Zaphrentis ambigua, Z. omaliusi, Chonetes, Productus* cf. *rotundus, Pustula, Schizophoria, Aviculopecten spp.*

Haw Bank Limestone. γ-C_1. 1,000 + ft. thick.

Dark grey to black, well-bedded compact argillaceous fragmental limestones, beds up to 3 ft. thick, with frequent micaceous shale and mudstone partings. Higher beds are lighter in colour, of coarser grade and are often crinoidal. Thicker shale bands near base and towards top shale beds up to 20 ft. Chert-strings and nodules throughout. " Zaphrentid phase " fauna in shale, rare " modified limestone " fauna throughout, *Solenopora* and bryozoan phase at top. *Syringopora* very common. Characteristic fossils: *Caninia cornucopiae, Cyathoclisia, Lophophyllum tortuosum, Palaeacis, Syringopora, Zaphrentis koninckı* forma typica, *Chonetes* of *C. papilionaceus*-group, *Schellwienella, Merocanites similis.* In higher beds, *Solenopora,* Bryozoa, *Spiriferina octoplicata* mut. δ, *Cleiothyridina glabristria* and Ostracods.

Details of Faunal and Lithological Distribution

1. Upper Tournaisian*

Zonal Group γ-C_1

Haw Bank Limestone.—These, the lowest beds in the succession, crop out in a narrow belt along the axis of the Skipton anticline from Aireville Grange, on the line of the South Craven Fault System, to a point some distance east of Holywell Bridge, where they pitch below ground. They thus occupy a belt of country some 4 miles long by $\frac{1}{2}$ mile in width, and stand out as a bold ridge known as Haw Bank which extends along most of their outcrop. The quarries on the northern side of this ridge afford the best of many good sections for the study of the limestones. The line of the quarries almost exactly follows the strike of the beds and for about 1,000 yards the limestones are exposed dipping N.N.W. at angles of from 45° to 70°. Other good exposures of these beds are found at Woodlands, Skipton Castle Woods, Storems Laithe, the quarries at Skibeden, High Skibeden and Far Skibeden and in the Holywell railway cutting where upwards of 180 ft. of beds are exposed. In Halton Gill, on the axis of the main anticline, a small exposure of dark limestones is believed to belong to this horizon, forming an inlier in the Halton Shales-with-Limestones.

The lowest beds (**99, 100**)** in Haw Bank Quarries, not far from the lowest exposed beds of the Haw Bank Limestone, are black limestones with shale beds often several feet thick. These are

* The divisions between Tournaisian and Viséan and between Lower, Middle and Upper Viséan are taken at breaks in the succession due to crustal movement. Thus the boundary between Tournaisian and Viséan is at the Mid-Dinantian line of movement (C_1/C_2) as advocated by Dixon (1911). P_{1a} is included in the Middle Viséan since in most areas in the Central Province it is separated from P_{1b} by a break in the succession due to crustal movement.

** Numbers in clarendon type are numbers of fossil localities listed on page 41 and shown on the map (Plate 1).

the most fossiliferous beds and contain the fauna later referred to as the *Cyathoclisia* fauna. The beds exposed in Haw Bank West Quarry in the quarry face north of Rock Cottage are of slightly different facies since they are massive lighter grey limestone, with, in places, little or no bedding and little shale. No identifiable fossils have been collected. The upper beds of the Haw Bank Limestone are seen at Holywell Bridge where the series contains thick limestones and beds of shale up to five feet thick. The shales contain an abundant Zaphrentid fauna. To the west of the Haw Bank Limestone outcrop, the top of the limestone series is represented by two beds which have not been recognized elsewhere. The best exposures are in the cliff under Skipton Castle walls to the south of the canal. Skipton Castle stands on a crag composed of limestone 30 feet thick, resting on a shale about 30 to 50 ft. thick. The limestone is sharply folded into a monocline and in the bend of the fold the shales are thickened by packing. This section was used by Marr (1899) to illustrate the thickening of both limestone and shale beds consequent on movement. On the northern side of the anticline at the point where Sougha Gill enters Eller Beck the shales are exposed dipping northwards at 60° with the limestone immediately above them. These beds are not fossiliferous and have not been traced eastwards. It is suggested that the shales thin out and that the limestone becomes merged into the top of the Haw Bank Limestone.

Fauna (excluding *Solenopora* and Ostracod-Bryozoan beds):

? Amplexus sp., 99-101*
Caninia cornucopiae *Mich.*, 101
C. *cf.* cornucopiae *Mich.* (*cf. C. vesicularis* Salée), 101
C. dorlodoti *Salée*, 105
Clisiophyllum (Cyathoclisia) modavense *Salée*, 100
Cyathoclisia tabernaculum *Dingwall*, 99
Lophophyllum (Eostrotion) tortuosum (*Mich.*), 101
Michelinia favosa (*Goldf.*), 100
Palaeacis axinoides *Smyth*, 99
Syringopora distans (*Fisch.*), 100
S. favositoides *Vaughan*, 99
S. *aff.* θ *Vaughan*, 99
S. *aff.* ramulosa *Goldf.*, 99, 100
S. *cf.* ramulosa *Goldf.*, 99, 101, 104
S. *cf.* reticulata *Goldf.*, 100
Syringopora spp., 100, 101, 104
Archaeocidaris *cf.* urei (*Flem.*), 100
Archaeocidaris sp., 99
Fenestella nodulosa (*Phill.*), 99
Fenestella sp., 100
Bryozoa, 105
Athyrid, indet., 101, 104
Camarotoechia *cf.* pleurodon (*Phill.*), 100
Camarotoechia sp., 104
Chonetes *aff.* papilionaceus (*Phill.*), 104
Chonetes sp. nov.[1], 99, 100
Chonetes sp., 101, 104
Derbyia ?, 101
Productus (Dictyoclostus) sp., 104
P. (Krotovia) sp., 104
P. (Linoproductus) sp., 104
Productus spp., 99, 100, 104
Reticularia *aff.* elliptica (*Phill.*[2]), 99-101

* Numbers in faunal lists refer to fossil localities.

[1] A large thin-shelled species with a slightly convex ventral valve and concave dorsal valve; extending to 80 mm. in width; a typical length : breadth ratio is 44 : 70. A somewhat similar form was figured by Vaughan (1905, pl. xxvi, fig. 3) as *Chonetes* aff. *papilionacea* from the base of the C_2 zone at Cromhall, near Wickwar, Glos. (length-breadth ratio 40 : 70) and again F. W. Cope has collected another from γ-C_1 Beds of Vallis Vale Frome (length-breadth ratio 39 : 60). (C.J.S.).

[2] This species is not conspecific with *R. elliptica*, being less wide-shelled; length : breadth:: 29 : 32 whilst *R. elliptica* is 50 : 76 and has closer concentric ornamentation, but the apical plate-distribution and spine spacing are similar. (C.J.S.).

Zaphrentis ambigua *Carr.*, 99, 105
Z. ambigua var. α *Smyth*, 99
Z. delanouei *E. and H.*, 99, 105
Z. konincki *E. and H.*, forma typica *Carr.*[1], 99-101, 104, 105
Z. *cf.* konincki *E. and H.*, 101, 104
Z. konincki, var. nov.[2], 99, 100
Z. *cf.* vaughani *Douglas*, 105
Crinoid remains, including Poteriocrinus sp., 100
Reticularia ?, 100
Schellwienella ?, 104
Spirifer sp., 99, 104
Straparollus sp., *large form*, 101, 104
Merocanites similis (*Crick*)[3], 100
Bairdia sp., 100
Bythocypris sp., 100
Cytherella ?, 100
Trilobite fragments, 104

The Cyathoclisia beds.—These beds, the lowest with an identifiable fauna, are exposed in Haw Bank Quarries (**99, 100**). They have a characteristic fauna of *Cyathoclisia* (early forms), *Zaphrentis konincki, forma typica* and *var. nov.*, *Palaeacis*, *Chonetes sp. nov.* and *Reticularia* aff. *elliptica*. The fauna is of γ age, a transition fauna between Z and C.

Zaphrentis konincki beds.—The main fauna of the Haw Bank Limestone continues the phase of the γ beds, though in an impoverished form. *Syringopora, Z. konincki,* and *Schellwienella* are the common forms. The fauna is of C_1 age. Compared with C_1 faunas elsewhere it is remarkable for the absence of such forms as the large *Caninia, Michelinia,* the large forms of *Spirifer* and *Syringothyris*. It is therefore taken as a γ-C_1 fauna (compare the γ-C_1 fauna listed in 1933 by T. N. George).

At various horizons nodules of a more calcareous mudstone weather out from the surface of many of the argillaceous beds. Though the structure of these nodules cannot be ascertained they are suggestive of calcareous algae or *Spongiostroma*. There are also many masses of pellet-like bodies about ½ inch across, often closely packed on the bedding planes. The origin of these has not been determined.

The fauna at Holywell (**105**) near the top of the Haw Bank Limestone though of a "Zaphrentid phase" contains *Z. konincki, forma typica* and is retained in γ-C_1.

Solenopora and Ostracod-Bryozoan beds.—The uppermost beds of the Haw Bank Limestone are exposed in quarries between High and Low Skibeden. Two faunas have been collected. A quarry (**103a**) shows black fine-grained limestone containing abundant nodules of a calcareous alga *Pseudochaetetes* [*Solenopora*] *garwoodi* (Hinde) the identification of which has been kindly confirmed by Professor Garwood. Close at hand in a quarry (**103**) the fauna listed below has been collected. Ostracods,

[1] This species is definitely that described by Carruthers as *Z. konincki, forma typica*, although some specimens have slightly longer minor septa than the specimen figured by him as typical. The species is common at Tournai and is distinct from the variety *Z. konincki, forma* α common in the Z_2 beds of Bristol and the variety *Z. konincki, forma* β (=*Z. konincki*, var. *kentensis* Garwood=*Z. konincki*, var. *arnsidensis* Salée=*Z. konincki*, mut. C_2 Vaughan) common in the Michelinia beds (C_2) of Arnside.

[2] This variety while it has the shape of *Z. konincki, forma typica* is larger (length, 6 cm., width of calyx, 2 cm.), has longer minor septa (half the length of the major septa) and a more open fossula.

[3] The type-specimen of *Merocanites similis* (Crick, 1895) came from the Haw Bank Limestone of Haw Bank Tunnel.

notably *Glyptopleura costata,* and bryozoa are unusually abundant and *Cleiothyridina* [*Athyris*] *glabristria* and *Spiriferina octoplicata* (J. de C. Sow), mut. δ are common. The fauna is that of the *Solenopora* subzone (C_1) of the North-West Province (*see* faunal list in Garwood, 1912, p. 460).

The fauna from **103** includes crinoid stem columnals, Bryozoa, such as *Cystodictya sp., Fenestella membranacea* (Phill.), *F. nodulosa* (Phill.), *F. plebeia* M'Coy, *Rhabdomeson sp., Chonetes* cf. *papilionaceus* (Phill.), *Cleiothyridina* [*Athyris*] *glabristria* (Phill.), *Cleiothyridina?, Crania?, Daviesiella* cf. *comoides* (J. Sow.), *Derbyia?, P.* (*Pustula*) cf. *rugata* Phill., Productids, including *Productus* (*Avonia?*), *P.* (*Pustula*) *sp., Reticularia sp., Spiriferina octoplicata* (J. de Sow.), mut. δ Vaughan, *Tylothyris sp., Conocardium sp., Aclisina sp., Bellerophon sowerbyi* d'Orb., *Capulus sp., Euomphalus pentangulatus* J. Sow., *Straparollus sp.,* ostracods, including *Bairdia sp., Glyptopleura* [*Kirkbya*] *costata* (M'Coy) *Paraparchites* [*Leperditia*] cf. *okeni* (Mün.), *Paraparchites sp.* and Cochliodont fish teeth.

Halton Shales-with-Limestones.—These beds usually form the lower ground between the Haw Bank and Embsay Limestones and are often covered by drift. The best exposures are ranged along the courses of Eller Beck and Embsay Beck on the northern side of the anticline, and in the core of the anticline along Halton Gill. The thickness of these beds is approximately 1,600 feet in the north-west of the area. When traced eastwards they thin until at Halton Gill the maximum thickness is about 200 feet. On the south side of the anticline they are only exposed at the base of the Embsay Limestone in the lower reaches of Skibeden Beck and in the adjoining quarry (**95** and **95a**). In this area and at Skibeden their thickness is reduced to 50 feet or less.

An identifiable fauna has only been found in any abundance at two localities, one near the base of the series (**96**) and one near the top (**97**). The fauna near the base is a Zaphrentid fauna of C_1 age, rich in individuals but poor in species. *Cyathaxonia, Zaphrentis ambigua, Z.* aff. *omaliusi, Fenestella,* and badly preserved Productids are common. A feature of this fauna is the abundance of large forms of *Schizophoria resupinata.* The other fauna is a lamellibranch-gastropod fauna. From stratigraphical considerations it is probably of C_1 age, but it is not possible to date this accurately, as such a faunal phase has not been previously recorded from C_1. It should be noted, however, that the composition of the fauna resembles that of the C_1 reef limestones such as, for instance, the Waulsortian reefs of C_1 age at Maredsous, which contain abundant molluscs.

Fauna :

Cyathaxonia cornu *Mich.*, 97
Zaphrentis ambigua *Carr.*, 96
Z. *aff.* ambigua *Carr.*, 96
Z. *aff.* omaliusi *E. and H.*, 96
Zaphrentis sp., 97
Poteriocrinus ?, 96, 97
Archaeocidaris sp. (*spines and plates*), 96, 97
Ortonia carbonaria *Young*, 97
Fenestella *cf.* nodulosa (*Phill.*), 96
F. polyporata (*Phill.*), 96, 97
Fenestella sp., 96
Penniretopora sp., 96, 97
Rhabdomeson sp., 97
Camarotoechia *cf.* pleurodon (*Phill.*), 96, 97
Camarotoechia sp., 96, 97
Chonetes (Plicochonetes) *aff.*, interstriatus *Dav.*, 97
C. *cf.* laguessianus *de Kon.*, 97
C. (Plicochonetes?) *cf.* waldenburgianus *Paeck.*, 97
Chonetes sp., 97
Dielasma *cf.* lenticulare *de Kon.*, 97
Dielasma sp., 96
Cf. Productus (Chonetipustula) carringtonianus *Dav.*, 96
P. (Dictyoclostus) *cf.* rotundus *Garw.*, 97
P. (Dictyoclostus) sp. nov., 97
Productus spp. *including* P. (*Avonia*) *sp.*, *P.* (*Echinoconchus*) *sp.*, *P.* (*Linoproductus*) *sp.*, *P.* (*Pustula*) *sp.*, 96, 97
Reticularia sp., 96
Schizophoria resupinata (*Mart.*) [*abundant including large forms at* 96], 96, 97
Schuchertella sp., 96
Cf. Allorisma sulcata (*Flem.*), 96
Aviculopecten *cf.* deornatus (*Phill.*), 97
Aviculopecten *cf.* interstitalis (*Phill.*), 97
A. *cf.* murchisoni (*M'Coy*), 97
A. *cf.* stellaris (*Phill.*), 97
A. sp., 96, 97
Ctenodonta sp., 97
Edmondia *cf.* pulchella (*de Kon.*), 97
Edmondia sp., 96, 97
Lithodomus ?, 96
Modiola ?, 97
Nucula *aff.* gibbosa *Flem.*, 97
N. *cf.* luciniformis *Phill.*, 97
Nuculana *cf.* attenuata (*Flem.*), 97
Parallelodon *cf.* semicostatus (*M'Coy*), 97
Parallelodon sp., 97
Protoschizodus sp. nov., 96
Pseudamusium anisotum (*Phill.*), 97
P. *cf.* anisotum (*Phill.*), 96, 97
Pseudamusium sp., 97
Sanguinolites *cf.* walciodorensis *Hind* non *de Kon.*, 97
Sanguinolites ?, 97
Cf. Scaldia lambotteana *de Ryck.*, 97
Solenomya costellata (*M'Coy*), 96
Cf. Solenomya costellata (*M'Coy*), 96
Spathella tumida *Hind*, 97
Bucaniopsis sp., 97
Mourlonia sp., 97
Platyschisma tiara (*J. Sow.*), 96
Polyphemopsis sp., 97
Coelonautilus sp., 96
Bairdia sp., 97
Paraparchites *cf.* okeni (*Mün.*), 97
Paraparchites sp., 96

2. LOWER VISÉAN

ZONAL GROUP C_2-S_1

Embsay Limestone.—In the northern part of the area this limestone crops out in a well-defined belt, often forming a ridge, from near the Craven Heifer Inn on the Skipton-Grassington road, by way of Embsay and Halton East villages to Halton Gill. There are good exposures in Embsay Beck at the west end of the village and at Halton East Quarries, where the limestone is worked for roadstone in beds which reach 15 in. in thickness. Here also the upward passage into the Skibeden Shales-with-Limestones may be seen (**91**). At Halton Gill outcrops of the limestone occur both to the north and south of the main anticlinal axis (**92, 94**). From Halton Gill westwards the southern out-

crop of the Embsay Limestone is not so evident. It is however well exposed south of the Skipton-Draughton road (**95**) and in Skibeden Beck (**95a**).

Both the thickness and the character of the Embsay Limestone are very variable. Near Embsay it is 350 ft. thick, and at Halton East quarries about 230 ft., and here the lowest beds are slightly pebbly. This pebble bed is also seen at the north crop in Halton Gill. On the southern outcrop in Halton Gill the limestone is not more than 60 ft. thick and the lower part contains marked conglomerates. There is a very coarse conglomerate within a few feet of the base. Cobbles of limestone with cross-sections up to 1 ft. by 6 in., and black shale pebbles are set in a coarse crinoidal matrix with corals and brachiopods. At the base of the limestone there is a further breccia-conglomerate about 1 ft. thick. These breccia-conglomerates continue in the thin Embsay Limestone of the southern crop and are seen in exposures **95** and **95a**.

A thin section of the limestone from the old quarries west of Halton East (**91**) showed the rock to be finely bedded with rare angular quartz chips. The matrix is fine grained with traces of crinoid and foraminifera debris, and there is much dark, very fine-grained calcite mud, broken up by patches of clearer crystalline calcite. The bedding depends on the relative abundance of these two types of matrix.

The Embsay Limestone is not very fossiliferous except at two horizons, the *Rhopalolasma* beds at the base, intimately connected with the conglomerates, and the *Palaeosmilia* beds, the fauna found in the transition beds between the Embsay Limestone and the Skibeden Shales-with-Limestones. The fauna of the *Rhopalolasma* beds, which is mainly a coral one, is of lower C_2 age and may be compared with the fauna of the upper part of the Rush Conglomerate (Smyth, 1915). The fauna is most abundant at **106**, an old quarry near Stirton Cross Roads.

The *Palaeosmilia* fauna is found at the top of the limestone in Halton East Quarries (**91**). The beds there are shales and might quite justifiably be included at the base of the Skibeden Shales-with-Limestones. The fauna is again a Zaphrentid one with abundant *Cyathaxonia, Zaphrentis, Fenestella,* small *Chonetes, Composita ambigua* and various pustulose Productids. The early Clisiophyllids and the various forms of *Palaeosmilia multilamellatum* date the fauna as of upper C_2 age, that is, the base of the Δ horizon as redefined by Vaughan (1915).

Fauna:

Cf. Arachniophyllum simplex *Smyth*, 91, 92
Caninia sp. [*C. cornucopiae group*], 91
Caninophyllum *aff.* patulum (*Mich.*), 94
Cravenia sp., 92
Athyris *cf.* ingens *de Kon.*, 92, 94
Camarotoechia sp., 90, 91
Chonetes (Plicochonetes) *cf.* crassistrius *M'Coy*, 91
C. *cf.* laguessianus *de Kon.*, 91
C. *cf.* papilionaceus (*Phill.*), 91.
Chonetes sp., 91, 92

Cryptophyllum *cf.* caryophyllatum (*de Kon.*), 106[1]
C. enorme *Hudson*, 106
Cyathaxonia cornu *Mich.*, 90, 94, 106
C. *cf.* cornu *Mich.*, 91
Densiphyllum nodosum *Smyth*, 94, 106
Densiphyllum spp., 106
Koninckophyllum ashfellense (*Garw.*), 90
Cf. K. carlyanense *Smyth*, 91, 94, 95
Palaeosmilia *cf.* cyathophylloides (*Vaughan*), 91
P. multilamellatum *M'Coy* [Group B, *Garw.*], 91, 95, 98
P. multilamellatum *M'Coy, var.* fornix *Hudson*, 91
Rhopalolasma *aff.* sympecta *Hudson*, 95, 106
R. tachyblastum[2] *Hudson*, 90, 94, 95, 106
R. tachyblastum *Hudson* (*immature var.*), 94, 106
R. tachyblastum *cf.* sympecta *Hudson*, 90, 92, 106
Rylstonia tenuicolumna *Smyth*, 106
Syringopora *cf.* geniculata *Phill.*, 94
Zaphrentis *cf.* delépini *Vaughan*, 95, 95a, 106
Z. densa *Carr.*, 94, 106
Z. *cf.* densa *Carr.*, 95, 106
Z. enniskilleni *E. and H., aff. var.* enniskilleni *Lewis*, 92, 94, 98
Cf. Z. junctoseptata *Smyth*, 94, 95
Z. *cf.* lawstonensis *Carr.*, 90
Z. *aff.* parallela *Carr.*, 91
Poteriocrinus sp. *and other crinoid fragments*, 91, 94
Fenestella membranacea (*Phill.*), 91
Cleiothyridina *cf.* royssii (*Dav.*), 91
Composita ambigua (J. Sow.), 91
Daviesiella *cf.* comoides (*J. Sow.*), 91, 92
Dielasma hastatum (*J. de C. Sow.*), 92
D. *cf.* sacculus (*Mart.*), 91
Dielasma sp., 91
Productus (Krotovia) aculeatus (*Mart.*), 91
P. *cf.* concinnus *J. Sow.*, 91
P. (Pustula) *cf.* ovalis *Phill.*, 91
P. (Thomasina) pectinoides *Phill.*, 91
P. (Thomasina) *cf.* pectinoides *Phill.*, 91
P. (Pustula) *cf.* pustulosus *Phill.*, 91
P. (Pustula) pyxidiniformis *de Kon.*, 90
P. *cf.* redesdalensis *Muir-Wood*, 91
Productus spp., *including P.* (*Avonia?*) *sp., P.* (*Dictyoclostus*) *sp., P.* (*Echinoconchus*) *sp., P.* (*Eomarginifera*) *sp., P.* (*Linoproductus*) *sp., P.* (*Pustula*) *sp., P.* (*Thomasina ?*) *sp.*, 90, 91, 94
Reticularia sp., 91
Rhipidomella michelini (*Léveillé*), 91, 92, 94
Schellwienella ?, 91
Schizophoria resupinata (*Mart.*), 91, 92, 94
Spirifer *cf.* bisulcatus *J. de C. Sow.*, 90, 92, 94
Spirifer spp., 90, 91
Syringothyris elongata *North*, 91
Pterinopecten tessellatus (*Phill.*), 91
Bucaniopsis sp., 92
Straparollus sp., 91
Phillipsia ?, 91, 94
Deltodus, sp., 94

Lower Skibeden Shales-with-Limestones.—These beds are similar to the Halton Shales-with-Limestones but are better exposed. To the north of the anticline they may be studied in Embsay Beck above the village, in Rowton Beck, Eastby, where the thin limestones in the series are well exposed, in Berry Ground Beck, in Halton Gill, and in numerous isolated exposures on the slopes north of Draughton Bottom. Eastwards they are cloaked by drift. South of the Skipton-Draughton Road the best sections are in Skibeden Beck, in which the folding is finely displayed, and

[1] This locality, 700 yards S. 25° E. of Cross Roads, Stirton, is outside the area represented on the map. It is about 2½ miles west of locality 95.

[2] *Rhopalolasma spp.* and *Cryptophyllum spp.* were described by one of us (R.G.S.H. 1936) from Butterhaw Quarry, Gargrave, 3 miles W.13° N. of Skipton Church. The horizon is that of the Rhopalolasma beds of the Skipton area. The horizon is there stated as the top of the Tournaisian since the dividing line between Tournaisian and Viséan was taken as that of Vaughan (1915) and not that of Dixon (1911) adopted in this paper.

in Stoneacre Gill. No diagnostic fossils have been found. The age is taken as S_1 since the transition beds at the base have an upper C_2 (base of Δ) fauna.

Upper Skibeden Shales-with-Limestones.—The upper part of the series is distinct from the lower part and from the Draughton Limestone above. In most sections there is a considerable thickness of fine-grained silty limestones with brown dolomitic streaks. They are dolomitic mudstones of " lagoon phase " (Dixon, 1911), and are well exposed in Banks Gill, Potters Gill, Stoneacre Gill, Skibeden Beck (higher reaches) and Hambleton Quarry.[1] They are very variable in thickness and in some sections, as at Draughton, only a few feet of them occur between the Lower Skibeden Shales-with-Limestones and the Draughton Limestone. It is suggested that this thinning of the beds is due to erosion before the deposition of the Draughton Limestone. The maximum thickness observed is about 70 feet in Skibeden Beck. Their base is indefinite; they pass down by intercalation of shales into the Lower Skibeden Shales-with-Limestones. The green chloritic patches noted on p. 6 are common in the higher part of the limestones. They occur, among other places, at Hambleton and Wheelam Quarries and at Intake House Quarry. Microscopic examination of a section from Hambleton shows that the limestones are composed of detrital fragments of bryozoa, shells, often bored, foraminifera and crinoids, together with tiny angular quartz chips and grains of pyrites. The chlorite occurs in small patches often intimately associated with calcite. Its presence suggests the addition of some volcanic material to the sediment. As in all dolomitic mudstones of " lagoon phase ", fossils are rare. Though the index fossil has not been found, the horizon appears to be that of the *Beyrichoceras hodderense* subzone of the Pendle District and the lithology with its conspicuous yellow weathering is strongly reminiscent of these beds. A section in Skibeden Beck (**74**), not far below the Draughton Limestone, appears to belong to these beds. It has yielded no diagnostic fossils. The goniatites are unfortunately too badly preserved to be specifically identified. The fauna from **74** is as follows :—

Plant fragments, *Cladochonus crassus* M'Coy, *C.* cf. *bacillarius* M'Coy, *Poteriocrinus* ?, *Chonetes* (*Plicochonetes*) *sp.*, *C.* (*Tornquista*) *sp. nov.* [elongated hinge and sinus in dorsal valve. C.J.S.], *Lingula* cf. *mytiloides* J. Sow., *Aviculopecten sp.*, *Beyrichoceras sp.*, *Goniatites sp.*, Nautiloid, *Cyrtosymbole* (*Waribole*) *sp.*, *Griffithides* ?, and *Phillipsia sp.*

The Intake Limestone outcrops close to Intake House (**67**) and near Embsay Kirk (**69**). It is a fine-grained black limestone in the top beds of the Upper Skibeden Shales-with-Limestones. It contains abundant foraminifera and the fauna listed below. This fauna is without doubt the *Rylstonia benecompacta fauna* described

[1] In some instances these beds appear to have been included as the lowest beds of the Eastby Limestone on the 1" Geol. Survey Map Sheet 92 SE, 1878.

by one of us (R.G.S.H. 1926) from Rylstone Railway Quarry north of Skipton which occurs between a series of dolomitic mudstones below (the Rylstone Limestones) and a breccia-conglomerate above (the Skelterton Limestone). It has been described elsewhere (the Cyathaxonia beds of Rush and Loughshinny, Vaughan; in part the Cyathaxonia beds of Derbyshire, Sibly; the Merocanites beds of the Isle of Man, Lewis), but has been given various ages mainly in the Dibunophyllum Zone since it is of " Zaphrentid phase " and at first sight resembles the " Zaphrentid phase " faunas of that zone. The authors are, however, of the opinion that it is of S_2 age, but since the greater part of the evidence for this is obtained from other areas it is not discussed here. The Intake Limestone is only found in the north-west of the area. Elsewhere it is apparently cut out by the succeeding unconformity (*see* Fig. 3).

Fauna: *Caninia amplexoides* (group α) Wilmore, 67, 69, *C. amplexoides* (group β) Wilmore, 67, 69, *C.* cf. *amplexoides* Wilmore [cf. *Amplexus*], 67, *Densiphyllum bradbournense* Vaughan, 67, 69, *D. rushianum* Vaughan, 67, *Densiphyllum sp.*, 67, 69, *Michelinia tenuisepta* (Phill.), 67, *Rylstonia dentata* Hudson, 67, *Zaphrentis derbiense* Lewis, 67, *Zaphrentis spp.*, 67, *Phillipsia* cf. *aequalis* (von Meyer) (in laminated calcareous mudstone band rich in individuals immediately below coral bed), 67.

3. MIDDLE VISÉAN

ZONAL GROUP S_2—D_1

Draughton Limestone.—By reason of the great difference in structure on opposite sides of the Skipton Anticline, this limestone crops out in the north in a nearly continuous belt, while in the south the outcrops are broken and separated. From Tarn House by way of Eastby and Studfold the northern outcrop extends to the River Wharfe near Riddings, although it is much obscured in its eastern quarter by drift. Embsay Beck and Heugh Gill, together with several neighbouring quarries afford exposures and the bed may readily be followed by the distinct ridge which it forms and the swallow holes which are present in the limestone west of Embsay. South of Haw Bank the Draughton Limestone enters the district south of Skipton and extends unbroken, save by faulting, to Close House. Here it becomes involved in the area of intense folding and between Close House and Draughton a number of separate outcrops are brought in by folding on the slopes south of the Skipton-Draughton road (*see* Fig. 4). This frequent repetition by folding continues eastwards in the country between Draughton, Halton East and the River Wharfe north of Bolton Abbey.

The full succession in the Draughton Limestone occurs near Draughton and Hambleton. Westwards, owing to the succeeding

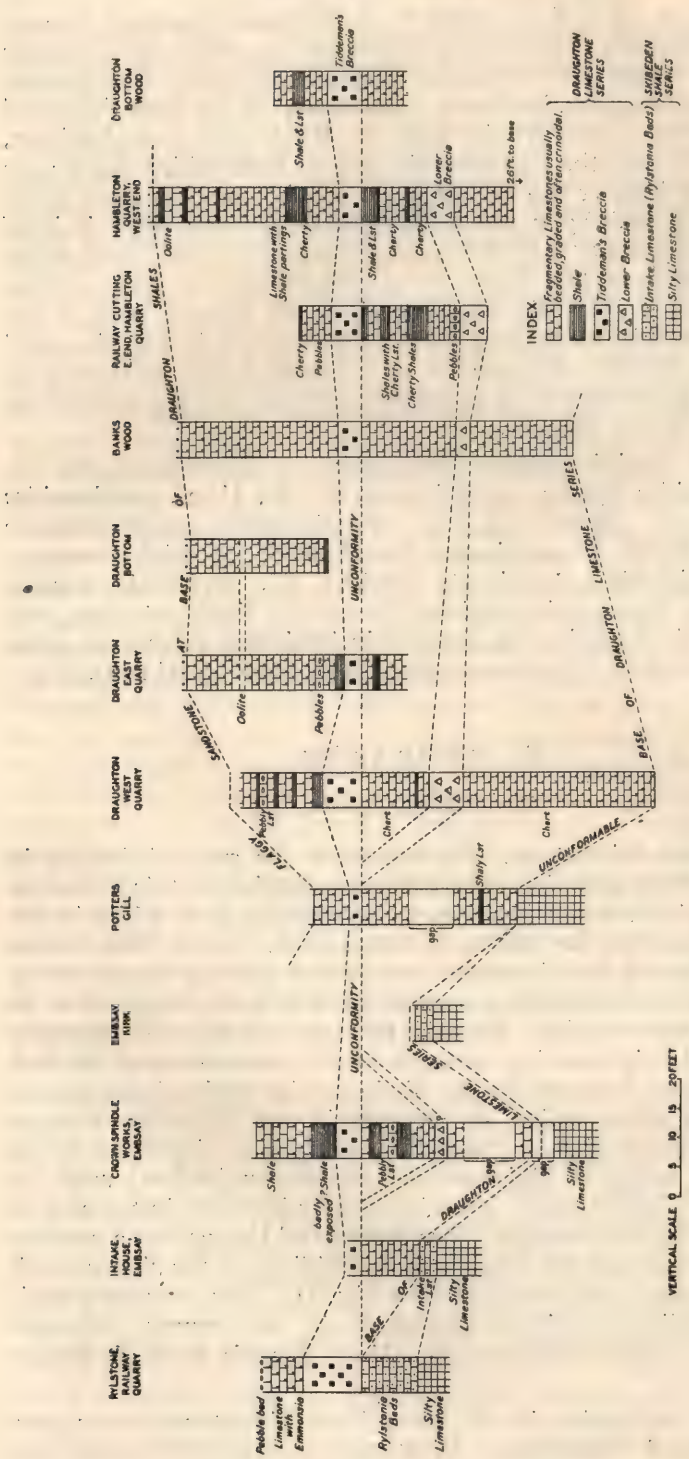

FIG. 3.—*Diagram showing variations within Draughton Limestone Series.*

unconformity, the full thickness is not exposed and to the east the same probably applies, though here the thick covering of drift makes observation in detail impossible.

As sections in the Draughton Limestone occur more frequently than in other members of the succession an attempt was made by detailed measurement to trace its lateral variation. The results are shown in Fig. 3, which demonstrates the variable nature of the limestone both in thickness and constitution. It has been possible to recognize a general vertical variation; the Lower Draughton Limestone, consisting of more massive crystalline fragmental limestones characterized by two marked beds of limestone breccia-conglomerate and with a tendency to be of standard coral-brachiopod phase, and the Upper Draughton Limestone, with darker and more thinly bedded fragmental limestones often containing well-rounded pebbles of black limestone of Zaphrentid faunal phase.

Breccia Beds (*Lower Draughton Limestone*).—The lowest beds, up to the Lower Breccia-Conglomerate, are featureless crystalline fragmental limestones with occasional chert nodules but with little shale. The Lower Breccia contains limestone pebbles, often banded, which average ½ in. in diameter, but may occasionally reach 6 in. across. They are angular to sub-rounded in shape and consist of finely fragmental limestone. They are sometimes fossiliferous; occasionally fragments of *Lithostrotion* form pebbles. The matrix is crinoidal and often dolomitic. Rarely are the limestone fragments silicified. Where the breccia is well developed it shows a marked base welded on to the fragmental beds below. The best exposures are in Draughton West Quarry (**77**), Banks Gill, Hambleton Quarry (**87**) (*see* Fig. 8), the quarries to the north of Bolton Abbey Station (**88**), and in the old quarry east of Eastby Methodist Chapel (**71**).

Upwards the fragmental limestones continue with the usual chert strings and nodules, while shale partings, themselves often cherty, divide the limestone posts. Occasional beds carry scattered limestone pebbles (*see* Fig. 3). At several places, as, for instance, in Draughton Quarries, erosional surfaces with higher beds truncating lower have been noted.

The Upper Breccia-Conglomerate is readily recognized and has proved invaluable in the interpretation of the structure of the area. It was first recorded by Tiddeman (1890) and in field work has often been referred to as "Tiddeman's Breccia." It is suggested that this name should be perpetuated in recognition of the great value of his work in the Craven district. The breccia varies in thickness up to 6 feet. The largest pebbles are at the base and consist of angular and subrounded fragments of finely fragmental grey limestones up to 12 inches across. The average fragment is from 1 to 3 in. in diameter. The pebbles are often impregnated or sometimes "edged" by a fine veining of silica, which weathers out from the rock in a characteristic network. The matrix consists

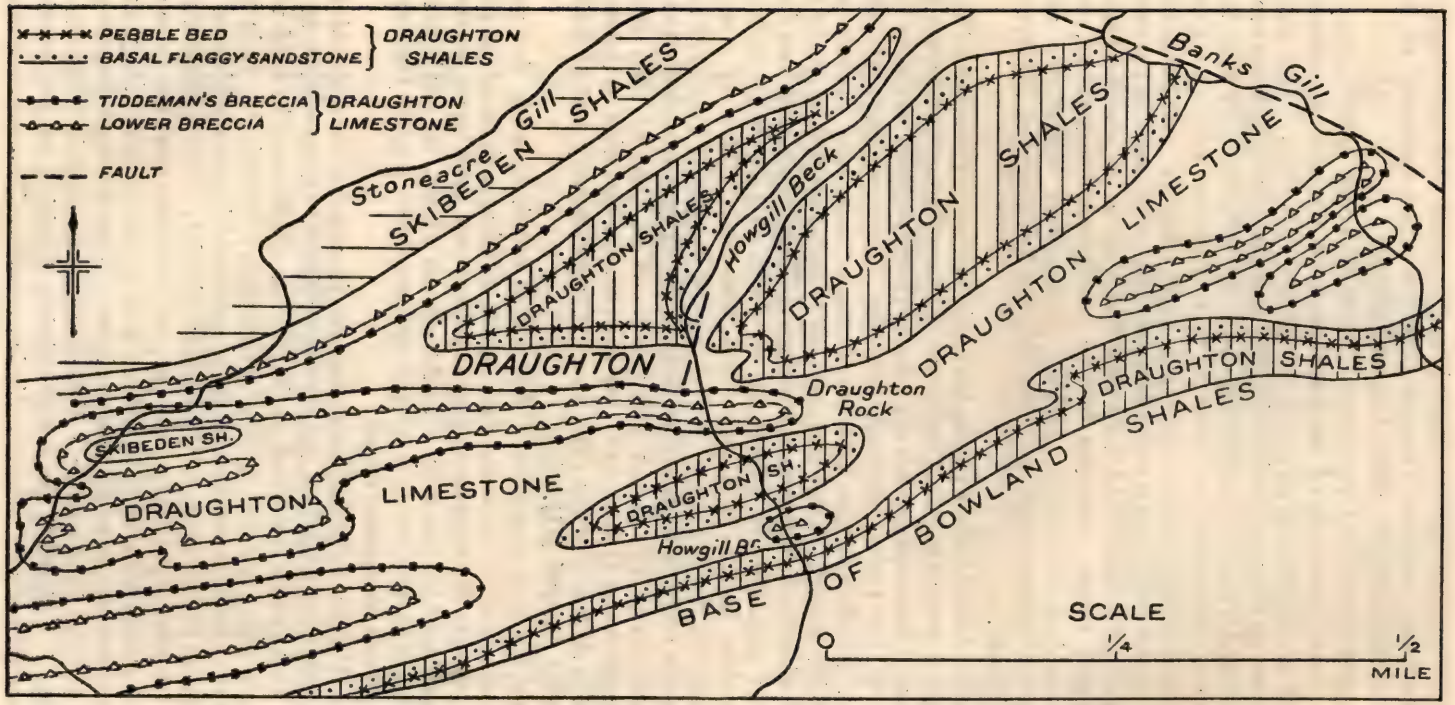

FIG. 4.—*Sketch-map showing the distribution of breccias and pebble-beds in the Draughton area.*

of finely comminuted fossil material, occasionally dolomitized. The base of the breccia is often sharp and irregular as in Draughton Bottom Wood and Draughton West Quarry (**77**), cutting down into the lower beds as much as a foot in six feet. The top of the breccia grades into a fine fragmental limestone similar to the matrix of the breccia. The breccia is found in the quarries at Draughton both behind the Methodist Chapel and at the west end of the village south of the Skipton road (Wheelam Rock and Hargreaves Kiln). Other good exposures are in the field immediately N.W. of Howgill Bridge, Banks Gill, Draughton Bottom, Hambleton Quarries, in the workings north of Bolton Abbey Station and in an old quarry on the east side of Halton Gill. North of Haw Bank exposures also occur at Intake House Quarry, Embsay, and in Embsay Beck at the Crown Spindle Works.

Many of the fossils found in the Lower Draughton Limestone, especially those in the Lower Breccia, are evidently derived. Such specimens as *Z. derbiense, Densiphyllum* and *Rylstonia* were probably derived from the underlying Intake Limestone.

Fauna:

Caninia *cf.* amplexoides (*Wilmore*), 86
Caninia sp., 72, 77
Cyathaxonia rushiana *Vaughan*, 83
Densiphyllum rushianum *Vaughan*, 75
D. *cf.* rushianum *Vaughan*, 73
Diphyphyllum lateseptatum (*M'Coy*), 86
Emmonsia parasitica (*Phill.*), 86
Koninckophyllum *cf.* *θ* *Vaughan* [early form], 76
Koninckophyllum sp., 77, 83
Lithostrotion *aff.* martini *E. and H.*, 75, 77
L. *cf.* martini *E. and H.*, 75, 77, 83, 86
L. *cf.* arachnoideum *M'Coy*, 77
L. minus (*M'Coy*), 77
L. sociale (*Phill.*), 77, 85
L. *cf.* sociale (*Phill.*), 76, 77
Lithostrotion sp. [*minus-arachnoideum group*], 77
Lithostrotion sp. [*affine-phillipsi group*], 77
Palaeosmilia murchisoni *E. and H.*, 87
Pseudocaninia sp., 75
Rylstonia sp., 86
Zaphrentis derbiense *Lewis*, 77
Poteriocrinus sp. *and other crinoids*, 75, 86, 88
Fenestella nodulosa (*Phill.*), 88
Fenestella sp., 81
Penniretopora sp., 88
Dielasma *cf.* abbreviatum *de Kon.*, 75
Dielasma sp., 88
Eumetria sp., 83
Leptaena *cf.* analoga (*Phill.*), 81
Productus (Krotovia) aculeatus (*Mart.*), 75, 76, 86, 88
P. (Avonia) *cf.* davidsoni *Jarosz*, 75
P. (Echinoconchus) elegans *M'Coy*, 75, 83, 81
P. (Overtonia) fimbriatus *J. Sow.*, 75, 76, 83
P. (Gigantella) latissimus *J. Sow.*, 81
P. (Plicatifera) plicatilis *J. de C. Sow.*, 81
P. (Echinoconchus) punctatus (*Mart.*), 76, 83
P. (Pustula) *cf.* pustulosus *Phill.*, 88
P. *cf.* redesdalensis *Muir-Wood*, 81, 83
P. (Dictyoclostus) *cf.* scoticus *J. Sow.*, 81
P. (Krotovia) spinulosus *J. de C. Sow.*, 86, 88
P. (Avonia) youngianus *Dav.*, 75a
P. (Eomarginifera) sp., 76, 83
P. (Krotovia) sp., 88
P. (Linoproductus) sp., 83, 88
Rhynchotetra ?, 88
Schellwienella sp., 75, 88
Schizophoria sp., 75
Spirifer *cf.* bisulcatus *J. de C. Sow.*, 81
S. *cf.* duplicicostus *Phill.*, 88

Polypora ?, 88
Actinoconchus planosulcatus (*Phill.*), 88
Actinoconchus ?, 76, 83, 88
Athyris expansa (*Phill.*), 82
Cf. Aulacophoria keyserlingiana (*de Kon.*), 75
Chonetes (Plicochonetes) crassistrius M'Coy, *var.* minima *Paeck.*, 88
C. *cf.* hardrensis (Phill.), 83
Chonetes laguessianus *de Kon.*, 75, 83
Aviculopecten sp., 88
Conocardium sp., 83
Parallelodon *cf.* bistriatus (*Portlock*), 88
Capulus ?, 83
Paraparchites cf. okeni (*Münster*), *and other ostracods*, 75, 83
Cyrtosymbole (Waribole) sp., 88
Griffithides *cf.* obsoletus (*Phill.*), 83
Phillipsia *aff.* derbiensis *Auctt.*, 83, 88
Proteus sp., 88

Emmonsia beds (*Upper Draughton Limestone*).—Although *Emmonsia parasitica* is not confined to this horizon it is the most characteristic fossil and serves to distinguish this set of beds. They are very variable. The lower part consists of dark fragmental limestones, occasionally oolitic, with a brachiopod fauna near the base (**81**) and a bed containing goniatites near the top (**84**, **78a**, **81a**). Behind the Crown Spindle Works, Embsay (**68**) one bed is rich in foraminifera. These beds pass upwards into thin crinoidal limestones with mudstone and shale partings, and often with black limestone pebbles. (*See* Fig. 3). Towards the top of the group there is a pebbly limestone containing many fragmentary fossils, often silicified. This bed contains *Emmonsia, Cyathaxonia, Zaphrentis* and *Michelinia, Productus spinulosus, P. elegans, P. venusta* and *Punctospirifer*. Near Eastby (**71a**) a wall probably quarried at the adjacent exposures is built of this rock and contains abundant fossils.

Throughout the series there is evidence of minor erosional surfaces. The best exposures of these beds are in Hambleton, Draughton and Wheelam Quarries, Banks Gill, and near Eastby (**71a**).

Fauna:

Cyathaxonia rushianum *Vaughan*, 71a, 77
Densiphyllum sp. (cf. *D. bradbournense* Vaughan), 73, 77
Dibunophyllum *aff.* θ *Vaughan* [*early form*], 71a
ϕ *Vaughan* [*early form*], 71a
Diphyphyllum sp., 71a
Emmonsia parasitica (*Phill.*) ,71a, 77
Lithostrotion sp., 81
Michelinia tenuisepta (*Phill.*), 71a
Palaeosmilia *cf.* pendlensis (*Park.*), 71a
Zaphrentis enniskilleni *E. and H.*, *var.* nov., 73
Z. *cf.* oystermouthensis *Vaughan*, 71a, 77
Serpulid, 81
P. (Gigantella) *cf.* latissimus *J. Sow.*, 79, 81
P. (Eomarginifera) *cf.* lobatus *J. Sow.*, 79, 81
P. (Eomarginifera) lobatus, *cf. var.* flexus *Muir-Wood*, 79
P. (Plicatifera) plicatilis *J. de C. Sow.*, 81
P. (Echinoconchus) punctatus (*Mart.*), 77, 79, 81
P. *cf.* redesdalensis *Muir-Wood*, 81
P. (Dictyoclostus) *cf.* scoticus *J. Sow.*, 81
P. (Krotovia) spinulosus *J. Sow.*, 79, 81
P. (Echinoconchus) venusta *I. Thomas*, 79, 81
Productus spp. *including P.* (*Avonia*) *sp., P.* (*Buxtonia*) *sp., P.* (*Dictyoclostus*) *sp., P.* (*Echinoconchus*) *sp.*

Crinoids including Rhodocrinus ?, 72, 77, 81
Fenestella *cf.* nodulosa (*Phill.*), 81
F. *cf.* plebeia *M'Coy*, 77
F. *cf.* polyporata (*Phill.*), 77
Hemitrypa hibernica *M'Coy*, 81
Penniretopora sp., 77
Rhabdomeson ?, 77
Actinoconchus sp., 79, 81
Athyris *cf.* lamellosa (*Léveillé*) [*large var.*], 79
Brachythyris ?, 79
Camarotoechia sp., 72, 73, 79
Chonetes (Plicochonetes) *cf.* buchianus *de Kon.*, 79
C. (Plicochonetes) crassistrius *M'Coy, var.* minima *Paeck.*, 77
C. *cf.* papilionaceus (*Phill.*), 79
C. (Plicochonetes) sp., 72, 77, 79
Dielasma *cf.* gillingensis (*Dav.*), 72, 73
Dielasma sp., 73, 79
? Eumetria radialis (*Phill.*), 73, 77
Leptaena *cf.* distorta (*J. de C. Sow.*), 81
Lingula sp., 77, 81
Productus (Krotovia) aculeatus (*Mart.*), 77
P. (Avonia) *aff.* davidsoni *Jarosz*, 79.
P. (Echinoconchus) elegans *M'Coy*, 79, 81
P. (Overtonia) fimbriatus *J. Sow.*, 77, 81
P. (Krotovia) sp., P. (Linoproductus) sp., P. (Eomarginifera) sp., P. sp., P. (Pustula) sp., P. (Thomasina) sp., 73, 77, 79, 81
Punctospirifer sp., 71a, 77
Reticularia ?, 79
Schellwienella sp., 81
Schizophoria *cf.* resupinata (*Mart.*), 73
Spirifer *cf.* bisulcatus *J. de C. Sow.*, 81
S. *cf.* furcatus *M'Coy*, 81
Spirifer sp., 71
Streptorhynchus ?, 79
Aviculopecten sp., 81
Conocardium *cf.* rostratum (*Mart.*), 77
Parallelodon bistriatus (*Portl.*), 73, 77, 81
Agnesia sp., 81
Capulus sp., 72, 73
Mourlonia sp., 77
Worthenia *cf.* munsteriana *de Kon.*, 81
Poterioceras ?, 81
Goniatites sp., 78a, 81a, 84
Griffithides cf. obsoletus (*Phill.*), 77, 81
Griffithides sp., 73, 77, 81
Paraparchites sp., 77
Fish-teeth, 81

Draughton Shales.—These beds appear on the north crop only in Green Beck, Halton East, and even there they are poorly exposed. Along most of the northern limb of the main anticline they are doubtless cut out by the unconformity. In the south of the area they first appear at Close House, where only the sandy beds at the base are recognized. The same beds are seen at Skibeden Beck and Potters Gill, but eastwards progressively higher beds appear from beneath the unconformity until between Draughton and Bolton Abbey a considerable thickness is exposed in the cores of the synclines below the unconformity at the base of the Bowland Shales.

The best exposures are at Hambleton Quarry, where the shales with accompanying limestones are seen to conform to the folding of the Draughton Limestone below. Here some of the shales are distinctly cherty and carry phosphatic nodules up to 2 in. across. Other localities are Draughton Quarry and Howgill Beck above the quarry. (*See* Fig. 5). An interesting pebble bed occurs above the basal flaggy sandstones between Skibeden Beck and Hambleton Quarry. It contains black shale and grey fragmental limestone pebbles averaging ¼ inch, but reaching 1 inch in diameter, set in a calcareous and crinoidal shale matrix.

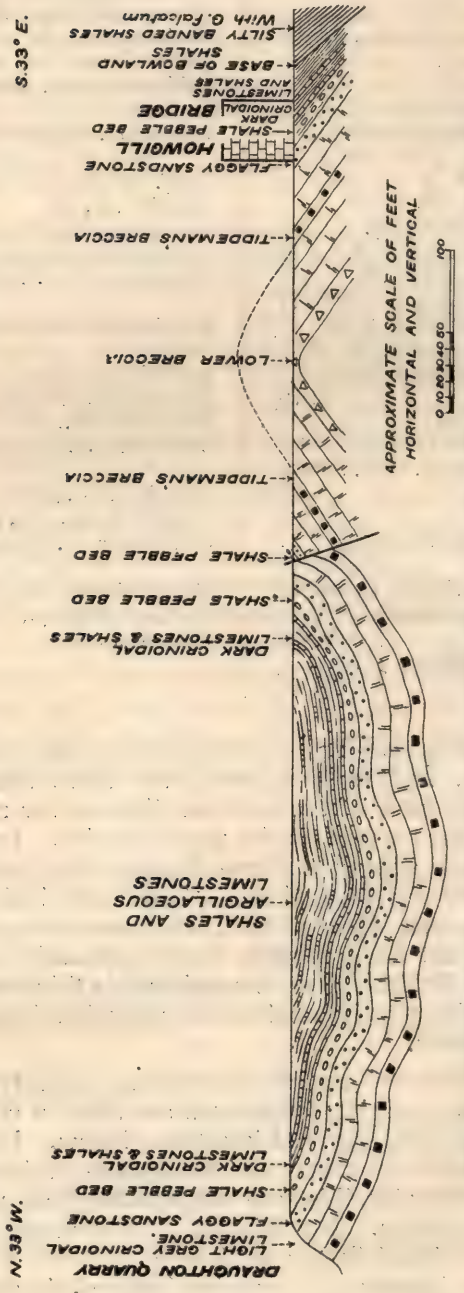

FIG. 5.—*Diagrammatic section from Draughton Quarry to Howgill Bridge along Howgill Beck.*

Emmonsia parasitica occurs in the bed in Banks Gill. A thin section of this pebble bed showed that the limestone pebbles are formed of fine-grained limestone rich in crinoid, brachiopod and goniatite debris. The matrix is a dirty brown calcite mud with rare tiny quartz grains.

A finely laminated limestone of this group from Banks Gill was clearly seen in thin section to be a detrital limestone. Abundant angular quartz grains and much broken fossil debris formed the bulk of the rock, the quartz being more frequent along certain bands, calcite in others. Foraminifera are abundant and the whole rock is finely crystalline in appearance.

The age of the Draughton Limestone and Shales:—The greater part of the Draughton Limestone is of D_1 age with *Dibunophyllum* θ and ϕ, *Koninckophyllum* θ, *Lithostrotion martini* group and *Palaeosmilia murchisoni*, though in the Lower Breccia there is an admixture of an S_2 fauna with *Lithostrotion minus-arachnoideum* group and L. *martini-sociale* group. Some or all of these, together with the *Rylstonia* fauna, may be derived. The Productids found in the Draughton Limestone are reminiscent of a brachiopod reef-fauna of D_1 age. It has not been possible to refer the beds to a position in the goniatite sequence. From a consideration of the relation of their stratigraphical position to that of surrounding areas it is probable that the Draughton Limestone is of Beyrichoceras Zone age, while it is possible that the Draughton Shales are of P_{1a} age since the main stratigraphical break at about this horizon occurs in neighbouring areas above P_{1a} and below P_{1b}, that is to say, above the Draughton Shales and below the Lower Bowland Shales.

4. UPPER VISÉAN

Zone of Goniatites crenistria s.l. (P_1)

Lower Bowland Shales.—The best sections in these shales are in Howgill Beck, above Howgill Bridge (**43a, 43.**), and in Banks Gill (**45, 46, 47**). The basal beds are often finely laminated and silty but are nowhere well exposed.

Posidonia becheri is common throughout the zone. Two distinct goniatite bands are recognized. Near the base is a band containing *G. falcatus* and *P. becheri* (**5, 35, 43a, 47.**) and near the top there is a band well exposed in Howgill Plantation (**43**) with *G. sphaerico-striatus, P. becheri* and *Pterinopecten mosensis*. *P. becheri* is here unusually abundant and well preserved.

The fauna is as follows:—*Chonetes spp.*, 47, *Orthoceras conquestum* de Koninck, 35, 47, *Dimorphoceras* ?, 42, *Goniatites elegans* Bisat, 45, *G. falcatus* Roemer, 5, 35, 43a, 47, *G. sphaerico-striatus Bisat*, 30, 43, *G.* cf. *sphaerico-striatus* Bisat, 45, *G. sp.* (crenistria group), 27, *G. sp.* (striatoid group), 11, 43b, *Sudeticeras*

hoeferi ? (Patt.), 43a, *S. sp.*, 42, *Posidonia becheri* Bronn, 4, 5, 13, 23, 27, 30, 35, 42, 43, 47, *P.* cf. *becheri* Bronn., 22-24, *Pterinopecten mosensis* (de Kon) (=*P. persimilis* Jackson), 42, 43.

The zone P_1 has been split up by Bisat (1928) into the following divisions:

P_{1c} *Goniatites sphaerico-striatus* subzone.

P_{1b} *Goniatites falcatus* subzone.

P_{1a} *Goniatites crenistria s.s.* subzone.

The *G. sphaerico-striatus* band occurs at the top of P_{1c} and *G. elegans* occurs below it in the same subzone (**45**). The *G. falcatus* band is taken as the top of P_{1b} and a fauna of *Goniatites sp.* (striatoid group) below it. The *G. sphaerico-striatus* band is of wide extent. It has been recorded by Bray (1927) from Lothersdale, by Waddington (1927) from Dinckley, by Hudson (1926) from Sunter Gill near Flasby, and by Jackson (1927) from Teilia Quarry, N. Wales. It is always accompanied by abundant *Posidonia becheri* and *Pterinopecten mosensis*.

It will be noted that no goniatites of the P_{1a} subzone have been collected from this area and that with the exception of the exposures in Banks Gill (**47**) and near Howgill Bridge (**43b**), where there are a few feet of shale containing *Goniatites sp.* [striatoid group] below the *G. falcatus* band, this latter band is at the base of the Bowland Shales. This is comparable to the position of the band in other areas. At Skelterton Beck, near Cracoe, shales with *G. falcatus* rest on the Skelterton Limestone (Hudson, 1926) and at Poyllvaish, Isle of Man, black limestones and shales containing *G. falcatus* and with a breccia bed rest on the irregular surface of the Poyllvaish reef limestone of P_{1a} age (Lewis, 1930).

Nettleber Sandstone.—The outcrop of this sandstone is limited to an area between Bolton Abbey and Draughton for both westwards and eastwards it is overlapped by the succeeding Middle Bowland Shales (Geol. Surv., 1935; Hudson and Versey, 1935). The best exposures are on the sides of Banks Gill near Haynholme and at Hambleton Beck near Bolton Abbey Station. The sandstone is of P_{1c} age since *G. elegans* occurs below it in Banks Gill (**45**) and *G. crenistriatus* occurs immediately above it in Haynholme Beck (**44**). As such it is the same age as the upper leaf of the Pendleside Sandstone of Pendle which, Mr. E. W. J. Moore informs us, occurs above *G. elegans* and below the *G. spiralis* zone.

Zone of Goniatites spiralis s.l. (P_2)

Middle Bowland Shales.—These beds form the lower part of slopes rising to the escarpment of the Millstone Grit. Formerly well exposed in Whinney Hill Brickworks (**18**) this section has now been much spoiled by tip-heaps. The best exposures on the south side of the area are in Close House Beck (**20, 21, 25**), in

Skibeden Beck (**31**) and on the banks of the Wharfe at Bolton Abbey (**61, 63**). Eastby Beck (Heugh Gill of 6″ Ord. Surv.) provides good sections on the north side of the area (**8-10**).

Numerous goniatite bands occur in the Middle Bowland Shales and more extensive collecting would probably enable an almost complete succession of the P_2 zone to be established.

Fauna:

Martinia *cf.* glabra (*Mart.*), 48
Martinia sp., 48
Actinopteria *cf.* flexuosa (*R. Eth. junr.*), 31
Aviculopecten spp., 48, 54
Posidonia cf. membranacea *M'Coy* [*elongate form*], 48a
Pseudamusium sp. nov., 31
Orthoceras spp., 20, 63
Beyrichoceratoides sp., 41
Goniatites granosus *Portl.*, 2, 3, 10, 15, 17, 20, 29, 48, 54
G. granosus *Portl.* [*early form*], 31
G. *cf.* granosus *Portl.*, 18
G. *cf.* maximus *Bisat*, 53
G. newsomi *J. P. Smith*, 18
G. newsomi *J. P. Smith* [*early form*], 29, 31, 53
G. *cf.* newsomi *J. P. Smith*, 8, 18
G. *cf.* spiralis *Phill.*, 10
G. subcircularis *Miller*, 21, 28, 63
Neodimorphoceras sp. [above 63]
Sagittoceras *cf.* coronula (*Roemer*), 61
S. meslerianum (*Girty*), 18
S. *cf.* meslerianum (*Girty*), 8
S. sp. nov., 20
S. sp., 15, 20
Sudeticeras crenistriatum (*Bisat*), 31, 44
S. *aff.* crenistriatum (*Bisat*), 18, 25, 42*
S. hoeferi (*Patt.*),41
S. *cf.* hoeferi (*Patt.*) 28
S. *aff.* hoeferi (*Patt.*), 31
S. splendens (*Bisat*), 9a
S. stolbergi (*Patt.*), 21, 25, 48a, 61, 63
S. *cf.* stolbergi (*Patt.*), 3, 18
S. *aff.* stolbergi (*Patt.*), 9, 28, 36

Three subdivisions of this subzone are possible and it is proposed to indicate them as follows:—

P_{2c} *Sagittoceras coronula* and *S. meslerianum* subzone.

P_{2b} *Goniatites subcircularis* and *Sudeticeras stolbergi* subzone.

P_{2a} *Goniatites granosus* and *Sudeticeras crenistriatum* subzone.

Subzone of P_{2a}: Two marked faunal horizons occur in this subzone in this area. Near the base a band occurs containing *S. crenistriatum, G. newsomi* [early form], *G. granosus* [early form] and *S.* aff. *hoeferi*. This band is just above the top of the Nettleber Sandstone in Haynholme Beck (**44**) and also crops in Skibeden Beck (**31**), Harry Wall Gill (**53**), Howgill Beck (**41, 42**) and in Whinny Gill Brickpits (**18**). Above this band is another containing *G. granosus* and *Sagittoceras sp. nov.* This occurs in Close House Beck (**20**), Banks Gill (**48**) and Heugh Gill (**10**).

Subzone of P_{2b} : The most easily recognized faunal band in this subzone is that of *Goniatites subcircularis* and *S. stolbergi*. It is usually found in a limestone or hard calcareous band towards the top of the subzone. It is well exposed at Bolton Abbey (**63**) where bullions containing many solid specimens have been collected, at Close House Beck (**21**), at Banks Gill (**48a**) and at Heugh Gill (**9**).

* Locality 42 covers several feet of beds at the junction of P_1 and P_2.

It also often contains an elongated form of *P. membranacea*. Below this band in Heugh Gill, Bisat has recorded *S. splendens* (**9a**) (1930).

Subzone of P_{2c} : This subzone contains *G.* cf. *newsomi Sagilloceras* cf. *coronula, S. meslerianum, Sudeticeras stolbergi*. The relationships of the various bands in this subzone has not been determined.

5. LOWER NAMURIAN

Zone of Eumorphoceras pseudobilingue s.l. (E_1)

This zone may be provisionally divided into the

E_{1c} *	Subzone of *Cravenoceras malhamense*	Upper Bowland Shales
E_{1b} *	Subzone of *Eumorphoceras pseudobilingue s.s. and Cravenoceras sp.*	
E_{1a} *	Subzone of *Cravenoceras leion* and *E. pseudobilingue* [early form]	Berwick Limestone

Berwick Limestone.—These beds are extremely variable. The crinoidal limestones which form the greater part of the series occur west of the Skipton area as a thin band exposed in Ramshaw Beck, Carleton, west of the River Aire. East of the Aire they have not been found until Howgill Beck is reached. From here eastwards they make a distinct feature along which are isolated exposures, while further evidence of the outcrop is provided by the many fragments thrown out of rabbit burrows. The thickness increases steadily after crossing the Skipton-Draughton road and exposures are good in Banks Gill (Hudson, 1930) and in the fields near Berwick West. The thickness here is about 200 ft. Eastwards the limestones again thin and are seen only in Harry Wall Gill, in the railway cutting S.E. of Bolton Abbey Station and in the banks of the Wharfe, 500 yds. N.E. of Bolton Abbey Station. At the last locality they have thinned to a mere 6-inch bed. On the north side of the area the limestones have not been recognized. Immediately below the limestones, shales with thin limestones contain *C. leion*, early forms of *E. pseudobilingue* and various other mollusca. The limestones contain a " Zaphrentid " phase fauna. Unfortunately no diagnostic forms have been found. The greater part of the limestone fauna has been obtained from Harry Wall Gill where below the thin black and white crinoidal limestone a series of grey limestones and black shales is exposed. These beds contain pebble beds and breccia, pebbles of calcareous shale and fine dark limestone being set in a matrix of shelly crinoidal debris. The pebbles are usually not more than $\frac{1}{2}$ in. across. The lowest of these beds in Harry Wall Gill may possibly belong to the top of the *G. spiralis* zone below.

* The subdivision of the zone E_1 into the subzones E_{1a}, E_{1b}, E_{1c} is provisional until the fauna is worked out in more detail. A subdivision is used in this paper since it is of value in dealing with the structure.

Fauna:

Lyssacine sponge, 52b
Caninophyllum ?, 52
Densiphyllum *cf.* bradbournense *Vaughan*, 52
Densiphyllum sp., 52
Zaphrentis sp., 52
Platycrinus sp., 52
Archaeocidaris *cf.* urei (*Flem.*), 52b
Spirorbis sp., 52b
Conodont ?, 52b
Polypora ?, 52b
Rhabdomeson sp., 52b
Actinoconchus planosulcatus (*Phill.*), 52
Brachythyris *cf.* integricosta (*Phill.*), 52b
Brachythyris sp. (*? B. ovalis group*), 52
Brachythyris sp., 52b
Camarophoria ?, 52b
Camarotoechia *cf.* pleurodon (*Phill.*), 52b
Camarotoechia sp., 52b
Chonetes sp., 52b
Cleiothyridina sp., 52b
Dielasma sp., 52, 52b
Martinia sp., 52, 52a, 52b
Phricodothyris ?, 52
Productus *cf.* concinnus *J. Sow.*, 52, 52a, 52b
P. (Pustula) *cf.* pustulosus *Phill.*, 49
P. (Eomarginifera) *cf.* setosus *Phill.*, 52, 52b
Productus sp. *including P.* (*Buxtonia*) *sp.*, *P.* (*Pustula*) *sp.*, *P.* (*Thomasina* ?) *sp.*, 49, 52, 52a, 52b
Reticularia sp., 52b
Schizophoria sp., 52
Spirifer *aff.* bisulcatus *J. de C. Sow.*, 49, 52, 52a, 52b
Actinopteria persulcata (*M'Coy*), 52
Leiopteria ?, 52
Posidonia membranacea *M'Coy*, 52*
P. obliqua (*de Kon.*), 52
Pterinopecten *cf.* mosensis (*de Kon*), 52*
Orthoceras sp., 39
Cravenoceras leion *Bisat*, 7, 14, 18, 39*, 49, 55*
Dimorphoceras sp., 39, 52
Eumorphoceras pseudobilingue *Bisat* (*early form*) 14, 33*
Eumorphoceras ?, 52
Sagittoceras sp., 39, 55*
Fish remains, 52, 52b

Upper Bowland Shales.—These beds occupy the higher slopes rising to the escarpment of the Millstone Grits. They are exposed in all the becks descending from Skipton Moor to Skibeden Beck. They are also seen in the west end of Chelker Reservoir. To the east they outcrop, greatly folded, along the line of the Lob Wood smash-belt and also occur in the railway cutting south-east of Bolton Abbey Station. Further exposures are found along the River Wharfe between Bolton Abbey and Bolton Bridge. Drift and landslips obscure much of the country between Embsay and the Wharfe in the north of the area, but the shales are found exposed at Heugh Gill and near Crag House with minor intervening outcrops.

Fauna: *Orthoceras spp.* 49, *Cravenoceras* cf. *leion* Bisat 58, 59, *C. malhamense* Bisat 57, *C.* cf. *malhamense* Bisat 38, 60, *C. sp.* (betweeen *C. leion* and *C. malhamense*) 32, *C. sp.* 33, *Dimorphoceras discrepans* (Brown) 32, *Dimorphoceras sp.* 33, *Eumorphoceras pseudobilingue* Bisat 1, 19, 32, 38, 40, 50, and Fish remains, 19, 34, 58. At most of the above localities *Posidonia membranacea* M'Coy was found.

* On the map a few feet of shales immediately below the Berwick Limestone are shown as Middle Bowland Shales, from which they are lithologically indistinguishable. At certain localities, however, they are found to contain such fossils as *Cravenoceras leion*, and *Eumorphoceras pseudobilingue* (early form) usually defined as E_{1a} in age. They are probably best considered as a passage fauna.

Skipton Moor Grits.—In this account the upper limit of the succession described is taken at the base of the Millstone Grits which cover Skipton Moor and Embsay Moor and by their fine opposed escarpments bear witness to the anticlinal nature of the structure. Wherever seen the junction of the grits with the Bowland Shales is abrupt and in several places leaves of grit come in and go out at the top of the shales in an irregular manner. The grits are themselves subject to considerable variation from south to north and their relationships are not fully worked out. Thus it appears that the lowest beds of the southern escarpment thin northwards and pass into shaly sandstones below the main escarpment on Embsay Moor. The beds forming the latter are probably equivalent to beds behind the main southern scarp on Skipton Moor.

There is some ambiguity about the position of the grit, bounded by parallel faults at Bolton Abbey. It has been mapped as a down-faulted mass of Skipton Moor Grits, but this involves a considerable throw of the faults. It is possible that it may be a grit within the Upper Bowland Shales. The objection to this is that it is not known elsewhere, even in the adjacent exposures, and this necessitates a rapid thinning of the bed. On the balance of evidence it is therefore included in the Skipton Moor Grits.

Sedimentation and Crustal Movements

The understanding of the structure of the area depends on the recognition of the several earth-movements which break the succession and their relation to the sedimentation. The succession may be divided into four sedimentation periods: the Haw Bank Limestone and Halton Shales (γ-C_1); the Embsay Limestone and Skibeden Shales (C_2-S_2); the Draughton Limestone and Shales (S_2-D_1) and the Bowland Shales (P_1-E_1). In general the sedimentation of each of these periods proceeded from deeper water to shallower water conditions, though throughout the succession is almost always of shallow water phase.[1]

Moreover each of these periods was initiated by earth-movement resulting in an unconformable base to each. That is to say three periods of earth-movement have been recognized, one at the base of the Embsay Limestone and therefore of C_1/C_2 age, one at the base of the Draughton Limestone and of S_2/S_2D_1 age and the third at the base of the Bowland Shales and of D_1/P_1 age with minor recurrences of this latter movement at two subsequent horizons, namely P_{1c}/P_{2a} and E_{1a}/E_{1b}. The C_1/C_2 movement is the mid-Dinantian unconformity which has been recognized elsewhere in Great Britain, notably in South Wales. The S_2/S_2D_1 break has not been previously recognized in Britain. The movements at the base of and within the Bowland Shales are considered to belong to one group of movements and have been detected in the Craven area (Dixon and Hudson, 1931).

[1] The bathymetric interpretation of the various rock types is based on the work of Dixon (1911) and other workers in the South-West Province.

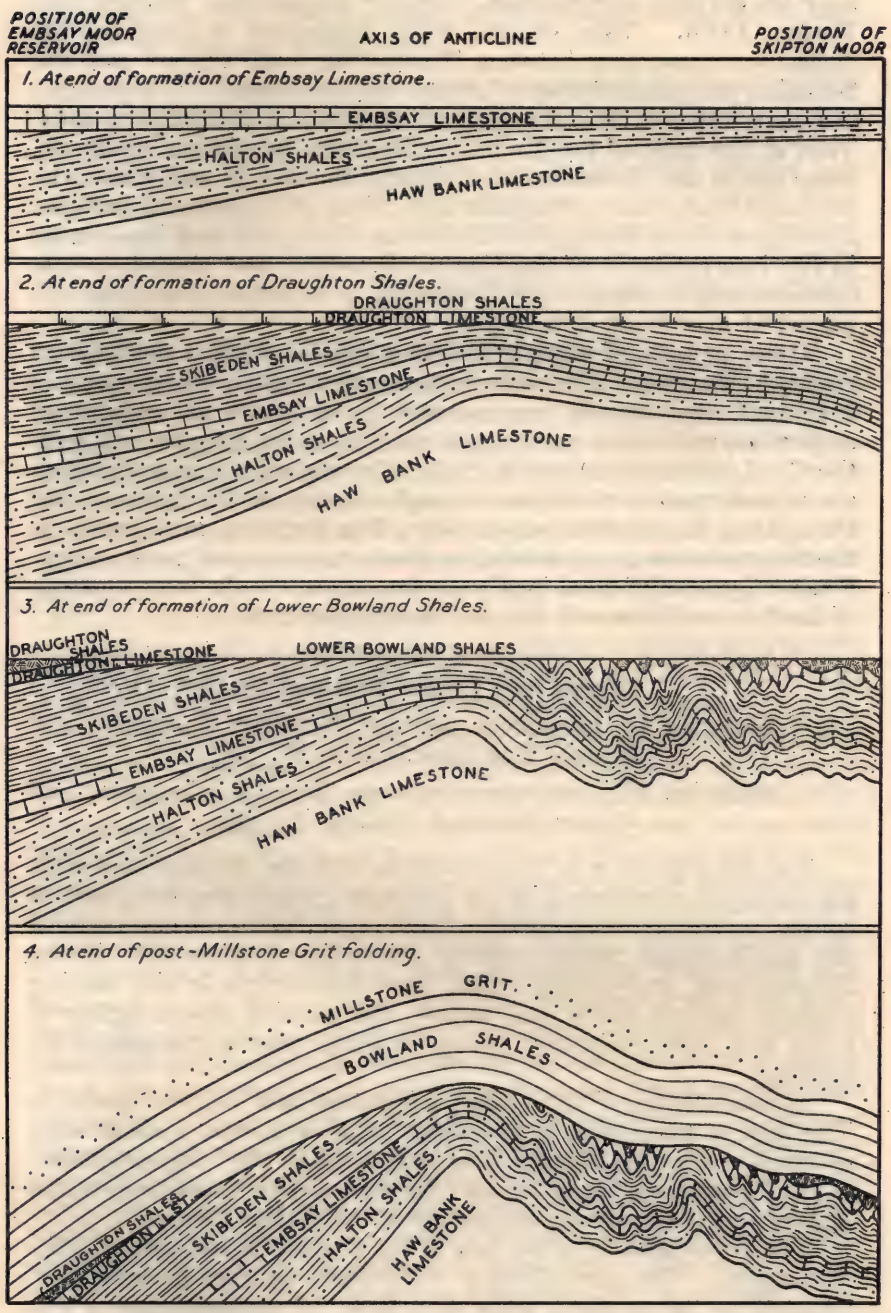

FIG. 6.—*Diagram showing stages in the evolution of the Skipton anticline.*

It has been shown that the Variscan folding of Central Europe may be divided into various orogenic phases (*see* Hudson and Turner, 1933). Two of the most important of these are the Nassauian movement between Tournaisian and Viséan, and the Sudetian movement between Viséan and Namurian. It is possible to equate these earth-movements with those in the Skipton area. That at the base of the Embsay Limestone is without doubt the same age as the Nassauian, and those at the base of and within the Bowland Shales are of Sudetian age. Since the movement initiated at the base of the Draughton Limestone (S_2/S_2D_1) is of importance in the interpretation of the Central Province, and since it is first demonstrated in the Craven Lowlands, it is proposed to term this period of movement Cravenian.[1]

These periods of earth-movements are not strictly confined to particular horizons. The periods throughout which the movements continued are usually represented by a series of condensed sequences, and this is particularly the case in the Skipton area with the C_1/C_2 (Nassauian) and S_2/S_2D_1 (Cravenian) movements which are represented by the breccia-conglomerates in the Embsay and Draughton Limestones respectively. The Sudetian movements in the Skipton area can, however, be shown to consist of three phases. The recognition of these is of great importance in the interpretation of the Craven Basin and they are therefore termed :—

Sudetian I, movement between Draughton Limestone and Shales and Lower Bowland Shales; D_1/P_{1a}.

Sudetian II, movement between Nettleber Sandstone and Middle Bowland Shales; P_{1c}/P_{2a}.

Sudetian III, movement between Berwick Limestone and Upper Bowland Shales; E_{1a}/E_{1b}.

The identification of the movements in the Skipton area with the orogenic movements in the Variscan geosyncline does not, of course, imply that they are of the same type. With the exception of the pre-Bowland Shales folding (Sudetian I) there are, in the Skipton area, movements which have their origin in the varying relation between basin and massif, the relative downsagging of basin and uplift of massif being in most cases accompanied by faulting.

Sedimentation of Haw Bank Limestone and Halton Shales.—The base of these beds is not seen. They represent a shallowing succession from the Cyathoclisia beds through the ' lagoon phase ' of the Solenopora limestone and the ostracod-bryozoan beds to the dolomitic and calcareous mudstones of the Halton Shales.

The unconformity at the base of the Embsay Limestone (C_1/C_2; *Nassauian*).—The area during γ-C_1 times appears to have been situated on the southern edge of a basin of sedimentation. The C_1/C_2 movement can best be considered as the result of the relative

[1]The orogenic phase known as the Selkian must be approximately of this age. Its age, however, has not been defined in the terms of the coral-brachiopod zones.

uplift of the area to the south. The γ-C_1 beds were slightly tilted and took on a northerly inclination. The thinning of these beds southwards is interpreted as due to their erosion prior to the deposition of the Embsay Limestone.

Attenuation against a shore line is suggested in the case of the Embsay Limestone, which is some 350 ft. thick in the north near Embsay but thins to less than 50 ft. with definite breccia-conglomerates at or near the base in the Halton Gill section and possibly to much less, still conglomeratic, to the south of Haw Bank. It is probable that the movement here has more than one phase, but it is impossible to distinguish them in the condensed Embsay Limestone. The Skibeden Shales again show an upward passage to shallower sedimentation ending in the S_2 dolomitic mudstones. These beds also thin to the south.

The general Upper Tournaisian-Lower Viséan sedimentation is therefore one of deposition in a basin, the northern border of which was probably the southern edge of the Lake District-Pennine massif and the southern border of which was not far to the south or south-east. An abrupt negative movement of the floor of the basin relative to the bordering massif was probably the main cause of the C_1/C_2 movement. It should be noted that this movement can be correlated with that seen in Crag Laithe Quarry (Hudson, 1927) to the north of Skipton and nearer the northern edge of the basin. Here C_1/C_2 faulting or steep monoclinal folding has resulted in boulder beds of great thickness between C_1 reef limestone and C_2 beds above, the latter with an Embsay Limestone fauna.

The unconformity at the base of the Draughton Limestone (*S_2/S_2D_1; Cravenian*).—The Draughton Limestone as shown in Fig. 3 rests unconformably on the Upper Skibeden Shales-with-Limestones. Similar sections have been recognized to the north of the area, as at Rylstone Railway Quarry (Hudson, 1926). The nature of the unconformity is best realised when the sedimentation of the Breccia Beds above (Lower Draughton Limestone) is understood since both are the result of the same movement. " Tiddeman's " breccia has been discussed by Marr (1899) who believed it to be due to movement. The mapping of the area, apart from the detailed examination of individual exposures, makes it clear that the breccia is a well-defined horizon present over a large area. The same applies to the Lower Breccia. The more likely explanation of their origin is that of Tiddeman (1890) who believed that these breccias were formed of material denuded by wave-action on adjoining deposits. Tiddeman further stated that these beds pass to the north into the reef limestones [of the Craven Reef Belt] and to the south-west (and probably to the south under the Millstone Grit) into the Pendleside Limestone. The work in the Skipton area has shown that not only does the Draughton Limestone include these beds, but that it is the equivalent of the full thickness of Craven Reef Limestone (several hundred feet) and Pendleside Limestone (350 feet). The Draughton Limestone is,

therefore, a condensed sequence deposited over an area relatively uplifted or stable when compared with the belts of Craven Reef Limestone and Pendleside Limestone deposition to the north and south of it. The uplifted area must have extended as far north as Rylstone and may have been composed of several folds. The uplift was initiated by the Cravenian movement(S_2/S_2D_1) and was responsible for the unconformity at the base of the Draughton Limestone. It should be noted that the Skipton area which, throughout Tournaisian and Lower Viséan times, lay to the immediate south of a rapidly subsiding area of mid-basin deposition, was in the Middle Viséan, an uplifted or relatively stable area.

The evidence afforded by the Draughton Shales at first suggests shallow conditions, indicated by the constant occurrence of the thin micaceous sandy flags above the Draughton Limestone, followed by pebble beds and crinoidal sandy limestones. Slightly deeper water is suggested by the black shales at the top of the series.

The unconformity at the base of the Bowland Shales (D_1/P_{1b}; *Sudetian I*).—At this point in the history of the area, a powerful set of earth-movements caused the development of the first recognisable anticline along an east-north-east line. This was evidently a considerable flexure (*see* Fig. 6) causing some increase in the tilt of the beds to the north of the axis, but giving rise to a main axis, to the south of which were numerous sharp folds of small amplitude arranged *en échelon* and whose crests were apparently almost all along the same horizontal plane. It is evident that the main mass of limestones to the north (or some unknown rock mass beneath) acted as a buttress against which the rocks were pushed, buckled and packed from the south, but which afforded protection to the measures in the area to the north.

It seems probable that some erosion took place along the axis of the anticline and in the folded area to the south, but the whole was very soon lowered below sea-level and deposition of the Bowland Shales of P_{1b} horizon commenced on the new floor. To the north in the unfolded area deposition was only slightly broken and resumption of sedimentation rapidly followed.

Thus only a slight disconformity is observable along the northern outcrop of the Draughton Limestone. This is essentially a strike section but it contrasts strongly with the sharply folded Draughton Limestone and Shales on which the Bowland Shales rest with marked unconformity in the Draughton area. Here again, although when individual sections are examined, there is considerable discordance, when viewed on a broad scale, the unconformity is not great. This points to much buckling of the beds below with no great regional uplift.

In other areas a similar state of affairs is suggested. At Rylstone and in the Isle of Man on the southern edge of the Reef Belt deposition of P_{1b} beds followed P_{1a} leaving little time-interval for the operation of the earth-movements which also occur in these areas.

Movements within the Bowland Shales (P_{1c}/P_{2a}; *Sudetian II and* E_{1a}/E_{1b}; *Sudetian III*).—When sedimentation was resumed following the pre-Bowland Shales movements (Sudetian I) the general succession up to the base of the Skipton Moor Grits was one of shallowing sedimentation. This was broken by two slight periods of movement, in each case accompanied by a change in the character of the sediments. The earlier, between Nettleber Sandstone and Middle Bowland Shales (P_{1c}/P_{2a}; Sudetian II) was preceded by the deposition of a sandstone (sandstone of emergence) which suffered erosion during the final period of movement. The later movement between the Berwick Limestone and the Upper Bowland Shales (E_{1a}/E_{1b}; Sudetian III) was of a similar nature. That the movement was active during the deposition of the Berwick Limestone is shown by the nature of the rock and the contained pebble beds. The culmination of the movement probably saw some erosion of the limestones themselves, before the deposition of the succeeding beds. In the area to the north both these movements have been recognized and are represented by boulder beds which are probably the result of faulting along the southern edge of the massif (Dixon and Hudson, 1931).

Post-Millstone Grit Movements.—The final important period of movement took place after the formation of the Skipton Moor Grits, and by analogy with the country to the south-east and east it most likely occurred at the close of the Coal Measure period and before the Permian rocks were deposited. In these movements the Bowland Shales and Millstone Grits were folded into a considerable anticline whose axis follows the earlier line of uplift (*see* Fig. 6). This folding tightened the limestones and shales below and produced the structures which, with but slight modification, are seen to-day. The Skipton Anticline was but one of many such folds in Ribblesdale and the Craven Lowlands, which with their complementary synclines are now arranged *en échelon*, following the older lines of movement.

Of later stirrings in the Earth's crust there is no direct evidence in the area but, if it be safe to make a comparison with the gentle easterly dip of the Upper Palaeozoic and Mesozoic rocks to the east, it may be suggested that the Skipton anticline was tilted gently eastwards and thereby received its slight pitch in that direction. Much of the faulting along north-west lines has been claimed as Tertiary in neighbouring areas and, whatever its age, it is clear that many of the faults which traverse this area are part of the same system.

Structure of the Area

Folding.—As already noted, the Skipton Anticline consists of a main anticline with a number of sharp subsidiary folds on its southern flank but preserving a steady dip on its northern side. The

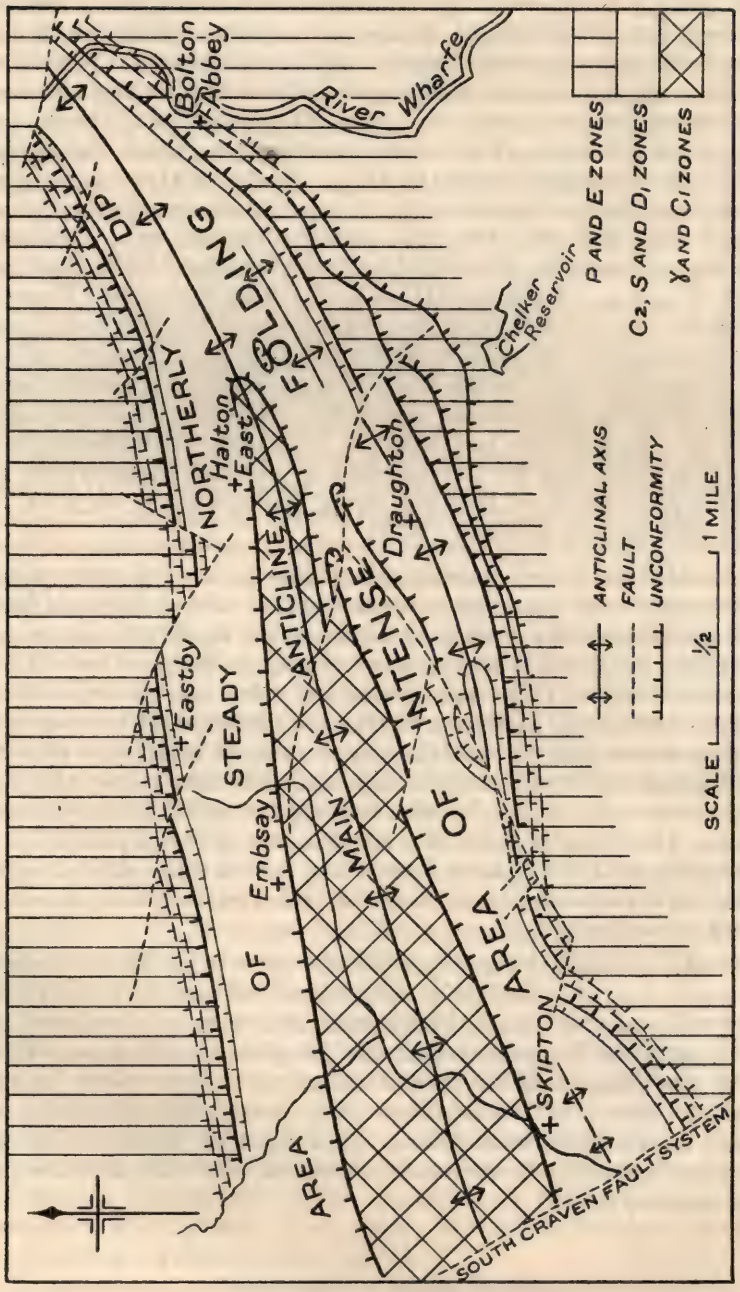

FIG. 7.—*Sketch-map showing the chief Structural Features of the area.*

main axis may be traced from Skipton to the River Wharfe north of Bolton Abbey, the direction being from west-south-west to east-north-east (*see* Fig. 7).

At Woodlands in the extreme west of the area the limestones are greatly folded and from here the axis of the fold trends eastwards, crossing Eller Beck in Skipton Woods. To the north of this the steady northerly dip is observed in the Haw Bank Limestones, but southwards towards the castle the beds, despite their general southerly inclination, roll considerably with minor anticlines, synclines, domes and basins. In places they are even vertical. The sections in Skipton Castle Woods demonstrate these features.

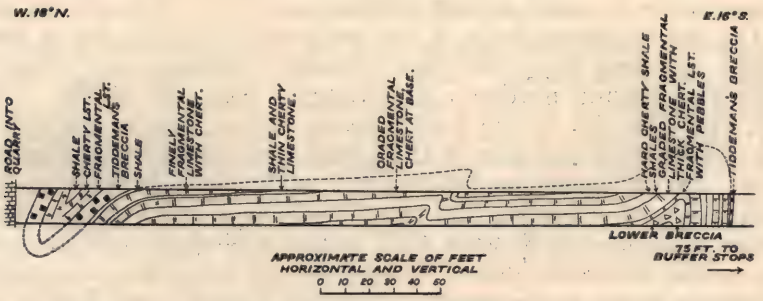

FIG. 8.—*Section along railway siding from Bolton Abbey Station to Hambleton Quarry.*

The actual direction of fold axes ranges approximately N.58°E. and therefore crosses the section obliquely.

The axis of the main anticline persists through the southern end of the old quarries at Storems Laithe, the strike ridges standing out well in the nearby fields, and must pass through the cutting just north of Haw Bank tunnel. Entering the Haw Bank Quarries the axis follows the southern edge of the quarries for some 500 yards, slightly sinuous, but maintaining a general east-north-easterly direction. Along much of this part of its course the actual crest of the fold appears to be broken and a fault-breccia and great slickensided planes may be followed behind the cottage at the west end of the quarries. On reaching Look-about, a prominent crag on the ridge of Haw Bank, the actual core of the fold makes a fine feature with cherty limestone showing opposing dips of 40° and 64° to the north and south on the respective flanks of the fold. Some indication of the intense nature of the folding may be seen in the manner in which the bedding planes in Haw Bank Quarry show lines of shear joints, filled with calcite, forming regular criss-cross patterns approximately at right angles.

Continuing eastwards the approximate position of the axis is marked by a line of exposures extending to the north of Skibeden Quarry. Here again considerable evidence of faulting along or near the axis is from time to time displayed in the shape of great shear planes exposed in the quarry and forming low angles with the strike. From the quarries the fold axis may be traced in a

general manner by numerous isolated exposures to near Holywell Bridge; but the actual turn-over is not again seen. At Holywell Bridge the disposition of the beds in the railway cutting shows that the axis crosses the railway about 130 yds. north-west of the railway bridge. The evidence also suggests some easterly pitch hereabouts. East of Holywell Bridge exposures are few until Halton Gill is reached. Here the opposed outcrops of the Embsay Limestone to north and south of the axis fix its position with accuracy. Much drift covers the ground between Halton Gill and the River Wharfe, at which point the outcrops of Draughton Limestone again enable the axis to be located. Furthermore the oncoming eastwards of higher beds along the axis of the anticline demonstrates its pitch in that direction.

On the northern flank of the main anticline the dip is very steady, all beds from the Haw Bank Limestone to Skipton Moor Grit having northerly dips ranging from 70° to 20°. (*See* Fig. 7). The dip in the higher strata is less than in the lower. The steady dip is best seen in Haw Bank Quarries where, for nearly a mile, the limestones are exposed with inclinations from 50° to 70°. Only one case of folding has been observed on the northern flank of the anticline—at Rowton Gill, where a shallow anticline was seen in the Skibeden Shales. Apart from the faulting a continuous succession exists in the neighbourhood of Embsay and Eastby.

On the southern flank of the anticline severe folding affects all beds from Haw Bank Limestone to Draughton Shales (Fig. 7). The Bowland Shales and Skipton Moor Grits on the other hand show none of the severe folding of the lower beds but only steady dips or gentle folds (Fig. 9). It is not possible to point to any specific folding as being due to the earth-movements of pre-Embsay Limestone or pre-Draughton Limestone times. The evidence for both these gentle movements lies in the thinning of the beds below, accompanied by the transgressions of the respective limestones as proved by the mapping. (*See* Plate I and Fig. 6). In the case of the earth-movements of pre-Bowland Shales times, however, the transgression of the Lower Bowland Shales over the beds below and the discordance of dip and strike displayed by the two series demonstrates the existence of important earth-movements at this time. It is, in fact, to this period that the main folding of the area belongs. (*See* Fig. 6).

The intensity of this folding is at its maximum near Draughton and repetitions of the Draughton Limestone thereabouts provide striking evidence of its character. The folding is complex, for not only are the beds affected by folds of large wave-length, but the individual large folds are greatly buckled as may be seen in the many quarry and natural sections near Draughton. (*See* Fig. 4).

The folded Haw Bank Limestones in Skipton Castle Woods have already been mentioned. The rolling of these beds is also apparent from a study of the dips in Skibeden Quarry, and

particularly in a small quarry-trial on the north side of the Skipton-Harrogate road—beside the second milestone out of Skipton. Other folds may be seen in the quarries at Far Skibeden, where the strike is oblique to that of the main folding, and in the railway cutting at Holywell Bridge. At the latter place, immediately south-east of the railway bridge, limestones with a prominent shale parting are folded into a sharp anticline and the pressure has been sufficient to induce strain-slip cleavage in the shale along the axis of the fold.

Whenever exposed the Skibeden Shales are much folded and even vertical. This is the case in Jenny Beck, in the stream north of Close House, Skibeden Beck, Stoneacre Gill, in the exposures north of Draughton Bottom and in Halton Gill.

Even more striking are the folds in the Draughton Limestone in the neighbourhood of Draughton. South-west of Close House this limestone is represented by a single outcrop in which the beds, though rolling, are yet not severely folded. East of this, however, the folding increases and three main belts of Draughton Limestone run along the moorside (Plate I). In many of the exposures of the rocks along these belts the beds themselves are crumpled into minor anticlines and synclines. This is well seen at Close House itself.

On reaching Draughton the numerous quarries and stream sections afford clear evidence of the nature of the folding. The presence of the breccia beds within the limestone at many places in the otherwise drift-covered area north of Draughton Bottom reflects the extent and nature of the folding. In particular the quarries in Draughton village may be quoted, and in addition the excellent sections along the courses of Banks Gill, Howgill Beck and Halton Gill. A study of this neighbourhood suggests that the folds are not continuous over long distances, but rather that a number of short pitching folds are arranged *en échelon* in a manner comparable with the disposition of the major fold axes in the Craven Lowlands. (*See* Figs. 1 and 4).

The heavily folded country appears to persist beyond Bolton Abbey to the edge of the area where the Draughton Limestone passes beneath higher beds. In the River Wharfe north of Bolton Abbey the same severe folding may be seen but over the valley sides of Wharfedale a heavy coating of drift effectively masks the solid rocks and renders impossible any attempt to trace the structure. Consequently the relationship of the highly folded area to the main anticline and the unfolded beds on its northern flank, so clearly developed in the west of the area, cannot be demonstrated in the east.

The Bowland Shales and Skipton Moor Grits dip steadily or roll gently save where disturbed by faults. Two smaller phases of movement are marked by minor unconformities revealed only by detailed mapping. They probably represent

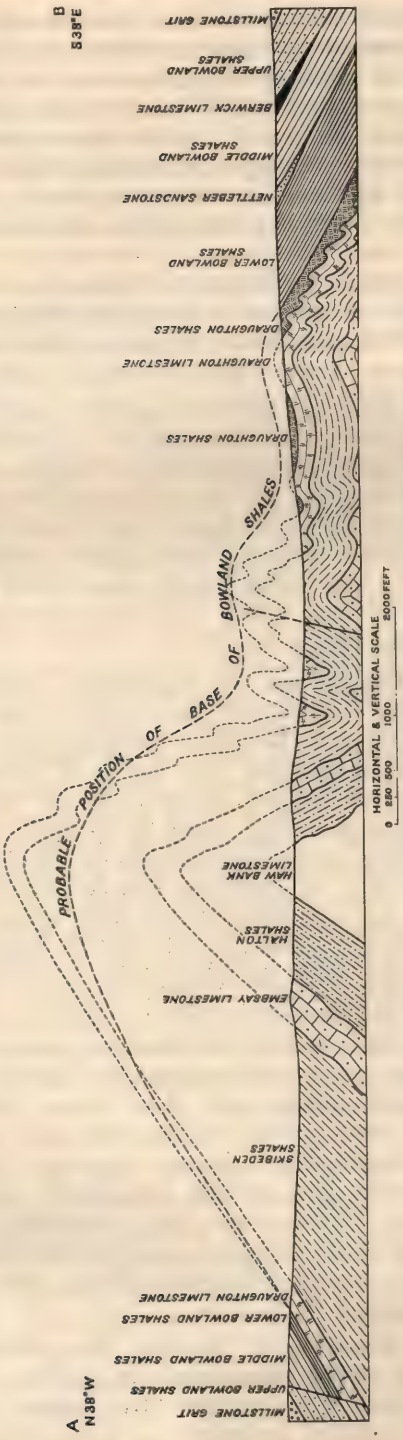

FIG. 9.—*Section across Skipton anticline along line AB on Map* (Plate I).

the final ripples of the great earth-storm which broke in pre-Bowland Shales times. Thus the lower of these, which occurs between the Nettleber Sandstone and Middle Bowland Shales is marked by the gradual transgression of the latter over the former beds due to slight differences in strike and dip. A similar slight divergence in strike and dip when traced over some distance reveals a further transgression by the Upper Bowland Shales over the Berwick Limestone. It is perhaps significant that in the case of the main pre-Bowland Shales unconformity as well as in the two smaller unconformities within the Bowland Shales the maximum thickness of measures occurring below each unconformity lies along a north-west to south-east line passing a short distance east of Draughton.

Faulting.—Compared with the folding the faulting is of less importance in this area. The details of the South Craven fault near Skipton on the western margin of the area are lost beneath the glacial drift and alluvium of the Aire Valley. The fact that structures do not appear to be continuous across its line suggests that the fault system is either intimately connected with the folding or there is a considerable lateral component in the faults.

A number of lesser faults which traverse the area have a similar south-easterly trend. Perhaps the most striking feature of these faults is the manner in which they break up the northern escarpment of the Skipton Moor Grits. Yet, save for a bunching of certain of the fractures in the Wharfe Valley below Bolton Bridge, the southern scarp of the Grits is unbroken by other than a few small faults. Thus apparently only one of the large faults which shift the beds in so conspicuous a manner between Embsay and Bolton Abbey breaks right across the anticline; the remainder split up and die away as they progress south-eastwards. Near Berwick East much faulting shifts the outcrops of the Bowland Shales and Skipton Moor Grits and in particular the fault-smash so well exposed in Lob Wood may be mentioned. From the rapid variations in the throws of the Banks Gill fault and its offshoots it appears likely that the lateral movement has been equally as important as the vertical, a condition which no doubt applies to other faults. Faults with similar trend cross Haw Bank and in one case at least the fault-plane is occupied by a vein of galena. This is exposed from time to time in the workings at the east end of Haw Bank Quarries.

The age of these faults is difficult to fix. That they are later than Millstone Grit times is clear, but it is not possible to be more precise. Faults with this trend have been claimed as Tertiary (Hudson, 1933) and though this may well be true, the intimate manner in which they are associated with the folding suggests that they may have been developed at about the time of the post-Millstone Grit earth-movements and perhaps have moved again along the already established lines at a later date.

A few faults have a north-easterly trend. Such is the fault which extends from near Close House to Draughton Bottom. Another crosses the River Wharfe near Bolton Abbey while yet others lie north of Halton East. They probably belong to the same set of movements as those with a north-westerly bearing. There is no evidence that they are other than simple tensional faults.

Finally, there are the many fault planes and surfaces of movement closely associated with the sharply folded rocks south of the main anticline. Such, for example, are the slickensided planes in Skibeden Quarry in the Haw Bank Limestone and in the Draughton Limestone at Wheelam Rock and Draughton Quarry. These are clearly of the same age as the folds and no doubt are further indications of the packing of the beds so evident in the intense folding. As such their initiation probably dates from pre-Bowland Shales times.

Summary

1. The mapping of the Skipton anticline on a scale of 6″ to the mile has demonstrated a succession of Upper Tournaisian, Viséan and Lower Namurian beds ranging in age from the γ-C_1 to E_1 zones.

2. The succession is grouped into four sedimentation periods:

   (d) The Bowland Shales (P_1-E_1).

   (c) The Draughton Limestone and Shales (S_2-D_1).

   (b) The Embsay Limestone and Skibeden Shales (C_2-S_2).

   (a) The Haw Bank Limestone and Halton Shales (γ-C_1).

3. Fossil assemblages such as characterize the Cyathoclisia beds (γ), the Solenopora beds (γ-C_1), the Rhopalolasma beds (C_2), and various goniatite assemblages of P_{1b} to E_1 age are described.

4. Three periods of crustal movement are recognized: Nassauian (C_1/C_2 age); Cravenian (S_2/S_2D_1 age) and Sudetian during which there was movement of D_1/P_{1b}, P_{1c}/P_{2a} and E_{1a}/E_{1b} ages. The Sudetian movements resulted in minor unconformities with the exception of that prior to the Bowland Shales (D_1/P_{1b}) which gave rise to the main folding of the Skipton anticline with sharp folding to the south and steady dips to the north of the main axis.

5. Renewed folding of the Skipton anticline took place in post-Millstone Grit times. The faulting is also of post-Millstone Grit age.

List of Fossil Localities

The numbers are those given on the Map (Plate I).
(N.B. a and b numbers are not shown on the map but approximate closely to their parent numbers).

Bowland Shales.

1. Embsay Beck, 108 yds. above northern entrance to water tunnel, Crown Spindle Works and 100 yds. south-east of Good Intent, Embsay.
2. Embsay Rock (above wall), 100 yds. above northern entrance to water tunnel, Crown Spindle Works and 108 yds. south-east of Good Intent, Embsay.
3. Embsay Beck, immediately north of northern entrance to water tunnel, Crown Spindle Works and 180 yds. south-east of Good Intent, Embsay.
4. Embsay Beck, immediately under northern entrance to water tunnel, Crown Spindle Works and 200 yds. south-east of Good Intent, Embsay.
5. In beck, 160 yds. N.34°W. of Embsay Kirk.
6. Lane, 205 yds. N.15°E. of Embsay Kirk.
7. Heugh Gill, 445 yds. N.51°W. of Methodist Chapel, Eastby.
8. Heugh Gill, 450 yds. N.54°W. of ,, ,, ,,
9. Heugh Gill, 460 yds. N.59°W. of ,, ,, ,,
9a. Heugh Gill, 460 yds. N.59°W. of ,, ,, ,, and 9 ft. below locality 9.
10. Heugh Gill, 440 yds. N.60°W. of ,, ,, ,,
11. Heugh Gill, 430 yds. W.7°N. of ,, ,, ,,
12. 70 yds. N.10°E. of Methodist Chapel, Eastby.
13. 160 yds. W.6°S. of Bark Laithe, and 270 yds. E.11°N. of Methodist Chapel, Eastby.
14. Stream, 200 yds. W.31°S. of Crag House, Eastby.
15. Stream, 200 yds. E.29°S. of Crag House, Eastby.
16. Tips from Old Shaft 1,450 yds. E.16°N. of Crag House, Eastby.
17. Stream, 70 yds. north of Great Wood Laithe.
18. Skipton Brick Pit, 200 yds. south of Parker's Hull (this pit covers a considerable area, including E_1 beds and not only P_2 beds as shown on map).
19. Jenny Beck, 500 yds. E.19°S. of Parker's Hull.
20. Stream, 190 yds. S.36°E. of Close House, Draughton.
21. Stream, 240 yds. S.37°E. of ,, ,, ,,
22. Stream, 250 yds. S.37°E. of ,, ,, ,,
23. Stream, 340 yds. S.37°E. of ,, ,, ,,
24. Stream, 350 yds. S.37°E. of ,, ,, ,,
25. Stream, 440 yds. S.33°E. of ,, ,, ,,
26. Stream, 490 yds. S.22°E. of ,, ,, ,,
27. Stream, 870 yds. E.27°N. of ,, ,, ,,
28. Stream, 800 yds. E.20°N. of ,, ,, ,,
29. Stream, 700 yds. E.14°N. of ,, ,, ,,
30. Skibeden Beck, 900 yds. S.11°E. of Currer Laithe, Draughton.
31. Skibeden Beck, 2,450 yds. E.7°N. of Parker's Hull, Skipton.
32. Skibeden Beck, 2,420 yds. E.4°N. of ,, ,, ,,
33. Skibeden Beck, 2,400 yds. E.2°N. of ,, ,, ,,

34. Skibeden Beck, 1,170 yds. S.5°E. of Currer Laithe, Draughton.
35. Potter's Gill, 1,870 yds. W. of Draughton Height.
36. Howgill Beck, 810 yds. W.24°S. of Lane End, Draughton.
37. Howgill Beck, 910 yds. W.33°S. of ,, ,, ,,
38. Howgill Beck, 600 yds. W. of Draughton Height.
39. Stream, 350 yds. N.50°W. of ,, ,,
40. Stream, 630 yds. S.52°W. of Lane End, Draughton.
41. Howgill Beck, 270 yds. N.25°S. of Lane End, Draughton.
42. Howgill Beck, 210 yds. W.26°S. of ,, ,, ,,
43. Howgill Beck, 160 yds. S.7°W. of Howgill Bridge, Draughton.

43a. Howgill Beck, 35 yds. S.22°E. of Howgill Bridge, Draughton.

43b. Howgill Beck, 20 yds. S.22°E. of Howgill Bridge, Draughton.

44. Stream, 230 yds. S.9°W. of Haynholme, Draughton.
45. Banks Gill (right bank), 525 yds. E.4°N. of Field House, Draughton.
46. Banks Gill, 700 yds. E.25°S. of Field House, Draughton.
47. Banks Gill, 200 yds. N.35°E. of Haynholme, Draughton.
48. Banks Gill, 250 yds. E.7°S. of ,, ,,

48a. Banks Gill, 360 yds. S.52°E. of ,, ,,

49. Banks Gill, 1,150 yds. E.13°N. of Draughton Height.
50. Northern corner of Chelker Reservoir.
51. Harry Wall Gill, 630 yds. S.17°W. of Bolton Abbey Station.
52. Harry Wall Gill, 440 yds. S.7°W. of ,, ,, ,,

52a. Harry Wall Gill (left bank), 350 yds. S. of Bolton Abbey Station.

52b. Harry Wall Gill, 390 yds. S. of Bolton Abbey Station.

53. Harry Wall Gill, 320 yds. S.2°W. of Bolton Abbey Station.
54. Railway cutting, 650 yds. W. of Devonshire Arms Hotel, Bolton Bridge.
55. Railway cutting, 570 yds. W.15°S. of Devonshire Arms Hotel, Bolton Bridge.
56. Hambleton Beck, 570 yds. E.9°S. of Bolton Abbey Station.
57. Tough Bank, River Wharfe, 480 yds. N.42°E. of Bolton Bridge.
58. The Strand, River Wharfe, 670 yds. N.18°E. of Bolton Bridge.
59. The Strand, River Wharfe, 830 yds. N.10°E. of Bolton Bridge.
60. Prior's Pool, River Wharfe, 850 yds. N.14°E. of Bolton Bridge.
61. Dixon's Deep, River Wharfe (right bank), 80 yds. E.N.E. of Bolton Abbey.
62. River Wharfe (right bank), 230 yds. N.14°E. of Bolton Abbey.
63. River Wharfe (left bank), 300 yds. N.49°E. of Bolton Abbey.

64. River Wharfe (right bank), 470 yds. N.49°E. of Bolton Abbey.
65. River Wharfe (left bank), 800 yds. N.47°E. of Bolton Abbey.
66. Pickles Beck, 1,300 yds. N.41°E. of Bolton Abbey.

Draughton Limestone and Intake Limestone.

67. Old Quarry, 240 yds. E.37°S. of Intake House, Embsay.
68. East side, Crown Spindle Works, 230 yds. E.43°S. of Good Intent, Embsay.
69. Old Quarry, 220 yds. W.11°N. of Embsay Kirk.
70. Old Quarry, 120 yds. E.16°N. of Methodist Chapel, Eastby.
71. Stream, 320 yds. E. of Methodist Chapel, Eastby.
71a. 230 yds. E. of Methodist Chapel, Eastby.
72. Old Quarries, 370 yds. N.63°E. of Parker's Hull, Skipton.
73. South side, Close House, Draughton.
74. *See* under Skibeden Shales.
75. Old Quarry, 150 yds. W.14°S. of Wheelam Rock, Draughton.
75a. 550 yds. S.55°W. of Wheelam Rock, Draughton.
76. Immediately N. of Howgill Bridge, Draughton.
77. Draughton Rock, immediately E. of Methodist Chapel, Draughton.
78. Howgill Beck, 260 yds. W.7°N. of Field House, Draughton.
78a. Howgill Beck, 270 yds. W.6°N. of ,, ,, ,,
79. Howgill Beck, 250 yds. N.68°W. of ,, ,, ,,
80. Banks Gill (left bank), 270 yds. N.68°E. of Field House, Draughton.
81. Stream, 235 yds. E. 16°N. of Field House.
81a. South side of Banks Gill, 240 yds. E.25°N. of Field House.
82. Old Quarry, 320 yds. E.32°S. of Field House.
83. Old Quarry, 400 yds. N.25°W. of Haynholme, Draughton.
84. Banks Gill, 600 yds. E.17°S. of Field House, Draughton.
85. Old Quarry, 830 yds. W.10°S. of Catgill, Bolton Abbey.
86. Hambleton Quarry (top beds), 300 yds. W. of Bolton Abbey Station.
87. Tiddeman's Breccia, north-eastern edge of Hambleton Quarry, alongside railway.
88. Old Quarry, 270 yds. N.55°E. of Bolton Abbey Station.

Skibeden Shales-with-Limestones.

74. Skibeden Beck, 860 yds. S.12°E. of Currer Laithe.
89. Banks Gill, 420 yds. N.82°E. of Field House, Draughton.

Embsay Limestone.

90. Quarry, 550 yds. N.41°E. of New Laithe, Halton East.
91. Old Quarry, 500 yds. N.48°W. of New Laithe.
92. Halton Gill, 130 yds. S.5°E. of Gill Head Bridge, Halton East.

93. Old Quarry, 850 yds. W.12°N. of Heskitt House, Bolton Abbey.
94. Halton Gill, at Waterfall, 980 yds. E.4°S. of Chapel, Halton East.
95. Old Quarry, 730 yds. N.50°W. of Close House.
95a. Skibeden Beck, 1,000 yds. W.20°S. of Low Skibeden.
98. Old Quarries, Elsey Croft Laithe, 850 yds. N.28°E. of Parker's Hull, Skipton.
106. Old Quarry, 700 yds. S.25°E. of Cross Roads, Stirton (this locality is west of the area represented on the map).

Halton Shales-with-Limestones.

96. Eller Beck, 425 yds. S.7°E. of Ellergill Farm.
97. Embsay Beck, 450 yds. N.9°W. of Embsay Station.
98. *See* under Embsay Limestone.

Haw Bank Limestone.

99. Haw Bank Quarries, 520 yds. S.17°W. of Embsay Station.
100. Haw Bank Quarries, 750 yds. E.20°S. of ,, ,,
101. Old Quarry, 300 yds. N. of Low Skibeden.
102. Quarry trial, 350 yds. W.15°N. of High Skibeden.
103. 250 yds. W. of High Skibeden.
103a. Old Quarry, 200 yds. E. of Low Skibeden.
104. 300 yds. N.30°E. of Far Skibeden.
105. Railway cutting, Holywell Bridge, 600 yds. E.21°N. of Far Skibeden.
106. *See* under Embsay Limestone.

Postcript.

The Solenopora band has recently been found in Haw Bank Quarries on the northern flank of the anticline. The three localities are :—850 yds. E.5°S., 510 yds. S.57°E., and 420 yds. S.47°E. of Embsay Station :—January, 1937.

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II.—VARIATION IN THE AMOUNT OF APATITE IN BRITISH TERTIARY IGNEOUS ROCKS

BY

J. E. RICHEY, M.C., Sc.D.

Text-figures 1—8.

THE crystallization of apatite in association with ilmenite often takes place at an early stage in the solidification of rock magmas. Such is the basis of the connexion suggested a few years ago by J. H. L. Vogt between the amounts of P_2O_5 and TiO_2 in igneous rocks generally[1]. In the case of the Tertiary igneous rocks of Britain a certain amount of early formed apatite is associated with the iron ore and ferromagnesian constituents. The mineral, however, is especially prevalent in the acid mesostasis of such rocks as tholeiites and quartz-dolerites, which represents the last portion of the magma to solidify, and in felspathic veins of late consolidation traversing crinanite sills. The concentration of apatite in the residual magmas is at variance with the conclusion that the Tertiary acid magmas are the result of the separation in bulk of these acid fractions. In the acid rocks we should expect to find that apatite is especially abundant. Yet the amount in the acid minor intrusions is somewhat less than in the quartz-dolerites, and in the acid plutonic rocks a marked poverty in the mineral, and in P_2O_5 in the chemical analyses, has been noted again and again. This inconsistency suggests a need for investigation, and the present paper though strictly limited in its scope presents certain main aspects of the problems involved, from the point of view of the differentiation theory.

If the amount of P_2O_5 is plotted against that of SiO_2 for all the analysed British Tertiary igneous rocks, as in Fig. 1, the result does not show any close grouping of the values, but in a general way the amount of P_2O_5 is greater in the intermediate rocks than in the basic and acid rocks. Grouping, however, becomes apparent if the two main magma-series recognized in the Tertiary province are taken separately. These series, as distinguished by Kennedy[2] following upon the initial conclusions of Bailey[3] and Thomas[4], include the following magma-types:

[1] Vogt, J. H. L. 'On the Average Composition of the Earth's Crust, with particular reference to the contents of Phosphoric and Titanic Acid,' Skrifter utgitt av Det Norske Videnskaps-Akademi, I Oslo, I. Mat.—Naturv. Klasse, 1931, No. 7, 1932.

[2] Kennedy, W. Q. 'Trends of Differentiation in Basaltic Magmas,' *Amer. Jour. Sci.*, vol. xxv, 1933, pp. 239-256.

[3] Bailey, E. B. and H. H. Thomas *in* 'The Tertiary and Post-Tertiary Geology of Mull', (*Mem. Geol. Surv.*), 1924, p. 13 *et seq.*

[4] Thomas, H. H. *in* 'The Geology of Ardnamurchan', (*Mem. Geol. Surv.*), 1905, p. 79. *et seq.*

Calc-alkaline Magma-Series:	Alkaline Magma-series:
Non-porphyritic Central or Tholeiitic Magma-Type	Hebridean Plateau or Olivine-basalt Magma-Type
Andesitic Magma-Type	Mugearitic Magma-Type
Acid Magma-Type	Trachytic and more acid Magma-Types

On the supposition that the evolution of each series is due to processes of differentiation, the two first-named magma-types are regarded as parents from which the more acid magmas were derived.

Differentiates branching from these main lines of descent are held to form other magma-types, namely, the Porphyritic Central and the Eucritic, the latter belonging to a magma-series which also include an ultrabasic (Allivalitic) magma-type. The Porphyritic Central magma-type is exemplified in the felspar-phyric basalts and dolerites, the Eucritic in the gabbroic rocks generally.

The amount of P_2O_5 relatively to that of SiO_2 is plotted in Figs. 2, 3 and 4 for the above magma-series and magma-types, and for certain ring-dykes of Mull in which differentiation *in situ* has occurred. It is to be noted that the values on Fig. 2 for the Calc-alkaline magma-series have reference to volcanic and hypabyssal rocks only. The acid plutonic rocks, which are usually included in this magma-series, are treated separately (Fig. 4). Further, on Fig. 4, as will be mentioned more specifically later, certain basic plutonic rocks are admitted which have been grouped by Bailey and Thomas either with the Porphyritic Central magma-type or with the Normal magma-series of these authors (equivalent in large part to the Calc-alkaline magma-series).

In the case of the two main series, the Calc-alkaline and the Alkaline, the grouping is sufficiently close to warrant curves of variation being drawn (Figs. 2 and 3). Both curves show an increase in the amount of P_2O_5 from the basic to the basic intermediate rocks, which is especially abrupt for the Alkaline series, and a gradual falling off towards the acid end. It will be noted that the middle part of the curve for the Alkaline series lies well above that for the Calc-alkaline.

The curve of variation for the differentiated ring-dykes of Mull (Fig. 4) is based on only a few analyses, but it bears out the fact, apparent in the rocks, that apatite is most plentiful in the intermediate zone of these intrusions. The parent magma, quartz-gabbro in composition, is grouped in the Mull Tertiary memoir with the Normal series (i.e. Calc-alkaline series, as restricted by Kennedy) on grounds of composition, and belongs to the Non-porphyritic Central (i.e. the Tholeiitic or Quartz-doleritic) magma-type. The curve of variation, however, in

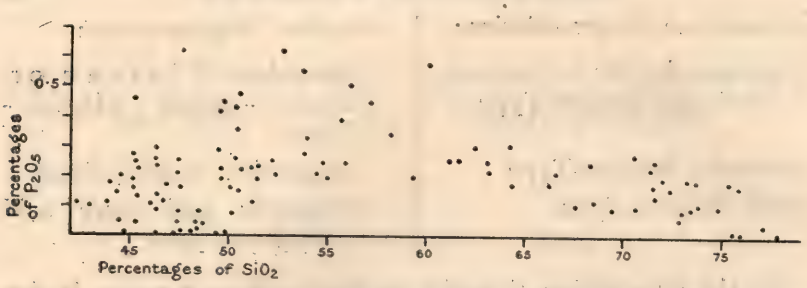

FIG. 1.—*Amounts of P_2O_5 relatively to SiO_2 in British Tertiary Igneous Rocks—lavas, minor intrusions, and plutonics.*

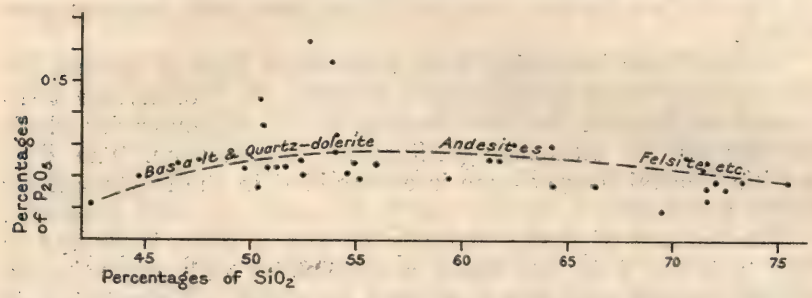

FIG. 2.—*Amounts of P_2O_5 relatively to SiO_2 in the Tertiary Calc-alkaline magma-series, Britain, restricted to lavas and minor intrusions.*

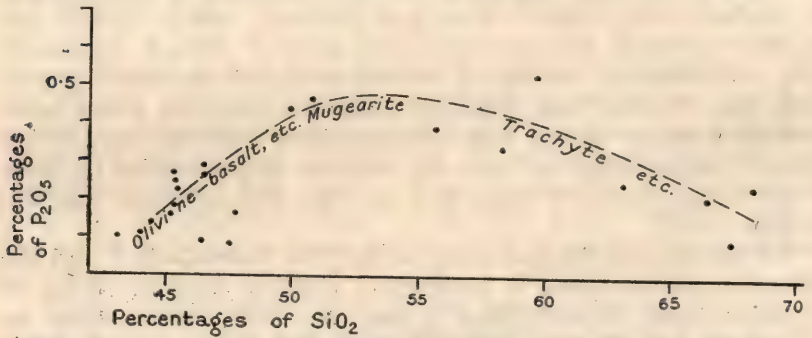

FIG. 3.—*Amounts of P_2O_5 relatively to SiO_2 in the Tertiary Alkaline magma-series, Britain.*

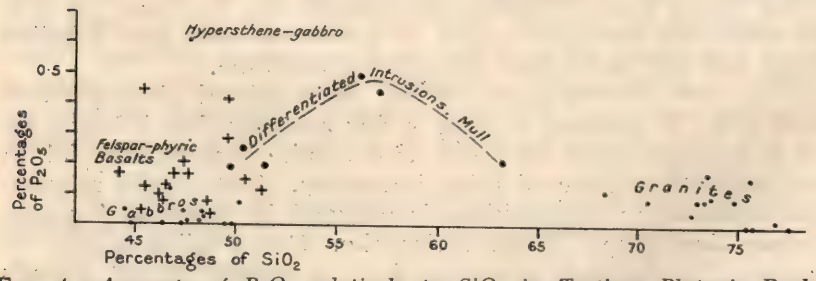

FIG. 4.—*Amounts of P_2O_5 relatively to SiO_2 in Tertiary Plutonic Rocks (indicated by dots) and Rocks of the Porphyritic Central magma-type (indicated by crosses), Britain.*

showing a much greater increase in P_2O_5 between the basic and intermediate rocks than that found in the Calc-alkaline series, resembles the curve for the Alkaline series. The reason for this resemblance may be an especial richness of the magma in volatiles, a characteristic of alkaline magmas which petrologists have often emphasized. This explanation, indeed, suggests a reason for the differentiation in bulk actually observed in Mull, an occurrence which is the *rara avis* of geology. Differentiation at the relatively high crustal level pertaining to the Mull examples would be facilitated by extreme liquidity of the parent magma due to the suggested richness in volatiles.

On Fig. 4, the plutonic rocks (diorites, etc.) for which a hybrid origin has been claimed are omitted. The gabbroic rocks include all the eucrites and also true gabbros with labradorite felspar, such as the Cuillin gabbro of Skye, the gabbro of Beinn na Duatharach, Mull, and a quartz-gabbro from Ardnamurchan, which have been grouped by Bailey and Thomas with their Porphyritic Central magma-type. All show a very low content of apatite and consequently of P_2O_5. The values lie well below those of the basalt lavas, etc., of Figs. 2 and 3. An exception to this rule is the high content of P_2O_5 in the analysed specimen of the hypersthene-gabbro of Ardnamurchan. This specimen however is for some local reason especially rich in apatite. The microscopic study of the gabbro has demonstrated that the rock is in general extremely deficient in this mineral.[1]

The acid plutonic rocks, the granites and granophyres, as already remarked, are also poor in apatite and show correspondingly low amounts of P_2O_5 in the chemical analyses.

The case of the gabbros is especially instructive. Poverty in apatite of rocks which are generally concluded to be due to crystal-accumulation, seems to indicate that gravitative settling of early formed crystals is not a factor which leads to enrichment in apatite, at any rate in this instance. Rather, the variation curves of Figs. 2, 3 and 4 suggest that P_2O_5 travels with the volatiles and becomes fixed as apatite especially in the intermediate rocks.

The decrease towards the acid end of the curves, particularly in the case of the acid plutonic rocks, is more difficult to understand. It is a problem for which the present restricted investigation can hardly be expected to provide a solution. Possibly the relative amount of lime to alkalies and to alumina is one of the main chemical factors involved. Possibly escape of P_2O_5 with other volatiles into surrounding rocks from the upper acid portions of differentiated bodies of magma is one of the physical reasons concerned. Indeed, enrichment in apatite in metamorphic aureoles around acid plutonic masses has been frequently noted.

[1] Thomas, H. H. *op. cit.*, 1930, p. 224.

It may be surmised that in the case of the acid minor intrusions, which are here taken to represent the acid end of the Calc-alkaline series, less opportunity would occur for an escape of P_2O_5 before crystallization set in than in the acid plutonic masses. The magmas responsible for the plutonic masses probably made their way upwards into their final position at a slower rate than the magmas forming the acid cone-sheets and dykes.

The values for the Porphyritic Central magma-type as represented by felspar-phyric basalts and dolerites are also given on Fig. 4. It will be seen that they do not show any tendency to linear grouping. This is another indication that variation in the amount of apatite does not depend upon crystal sorting, since the felspar-phyric rocks concerned are in all probability due to the separation of early formed crystals of basic plagioclase felspar.

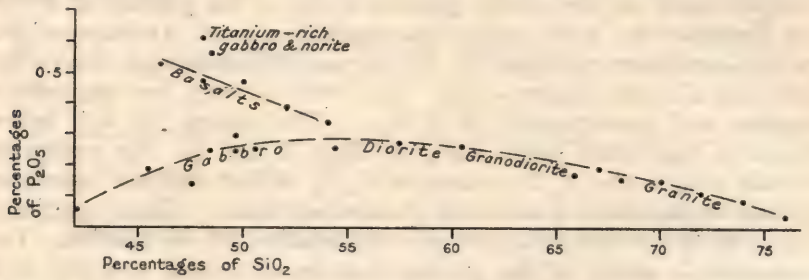

FIG. 5.—*World Averages of Amounts of P_2O_5 relatively to SiO_2 for certain rock-types, from estimates by J. H. L. Vogt and R. Daly.*

It is difficult to compare the results arrived at for the Tertiary igneous rocks of Britain with the world averages computed recently by Vogt. The range of Vogt's data is so wide, and various factors leading to the diversity of igneous rocks in nature in addition to fractional crystallization may well be involved. Lines of variation drawn from certain of Vogt's (and Daly's) results, however, are given on Fig. 5. Two points of similarity to the British Tertiary averages are that the content of P_2O_5 is much higher in the basalts than in the gabbros, and that there is a decrease in this constituent towards the acid end. A noteworthy difference is that the world averages for basalt and gabbro are much higher than in the case of the British Tertiary examples.

Vogt's main thesis, too, is based upon the conclusion that apatite is concentrated with ilmenite during the process of gravitative differentiation, whereas the Tertiary results suggest more particularly a connexion between P_2O_5 and the volatile constituents.

The relations between the amount of P_2O_5 and TiO_2 have been plotted on Figs. 6 and 7 for the two main Tertiary magma-series. The result in the case of the Alkaline series does not show any relationship; but that for the Calc-alkaline indicates a grouping suggestive of a regular variation in the proportion of the two constituents, which seems to warrant further investigation.

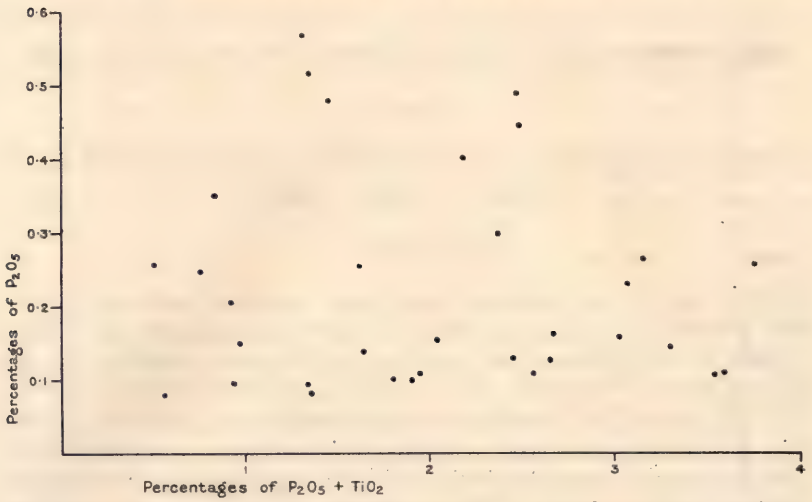

FIG. 6.—*Amounts of P_2O_5 relatively to P_2O_5 + TiO_2 in the Tertiary Alkaline magma-series, Britain.*

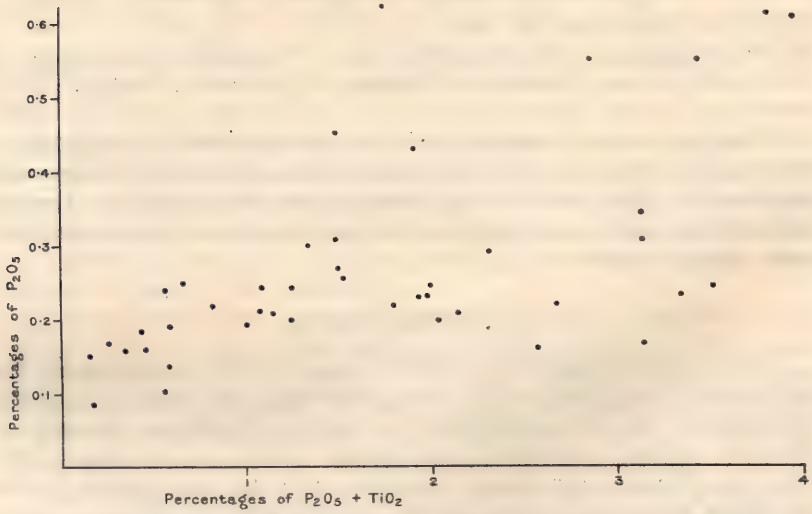

FIG. 7.—*Amounts of P_2O_5 relatively to P_2O_5 + TiO_2 in the Tertiary Calc-alkaline magma-series, Britain.*

The values for P_2O_5 : P_2O_5 + TiO_2 have therefore been calculated and plotted as ordinates against the percentages of silica as abscissae (Fig. 8). It will be noted that a tendency exists for the relative amount of P_2O_5 to increase with increasing silica, and that there is an antipathetic relation to the amount of TiO_2, which is contrary to Vogt's thesis. TiO_2 entering as it does into the ferromagnesian as well as the iron ore crystallization tends to be removed in the earlier stages, while the P_2O_5 tends to remain.

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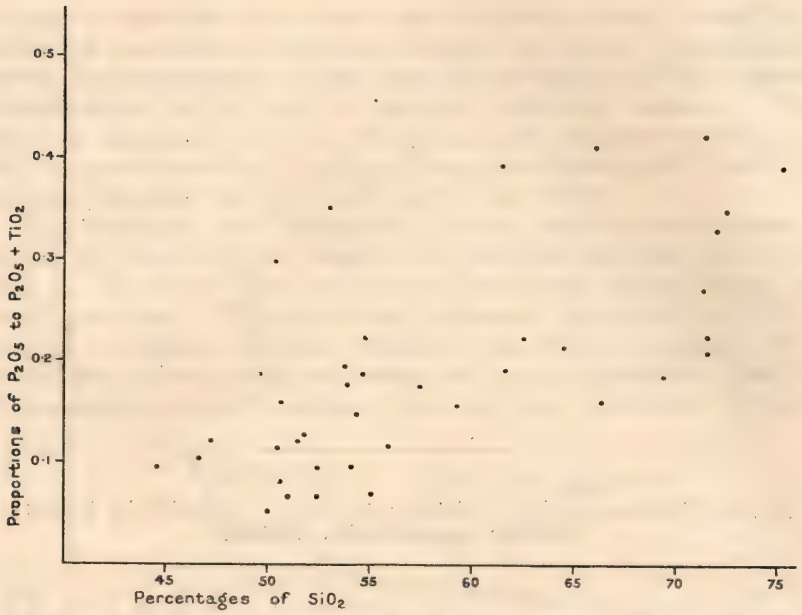

FIG. 8.—*Proportions of P_2O_5 to P_2O_5 + TiO_2 relatively to Percentages of SiO_2 in the Tertiary Calc-alkaline magma-series, Britain.*

Finally, it may be mentioned that the majority of the gabbroic rocks and all the acid plutonic masses show a marked poverty not only in P_2O_5 but also in TiO_2, whereas the felspar-phyric basalts and dolerites are sometimes rich in one or other of these constituents, rarely in both.

ACKNOWLEDGMENTS

The author is specially indebted to Dr. W. Q. Kennedy for suggesting lines along which progress might be made during the development of this investigation, and for constant discussion. He also wishes to express his thanks to Mr. S. Tomkeieff and Prof. A. Holmes for kindly allowing him to incorporate in the variation diagrams results from unpublished analyses in their possession.

III.—AN APATITE ROCK FROM DUMFRIESSHIRE

BY

W. Q. KENNEDY, D.Sc., WITH ANALYTICAL NOTES BY C. O. HARVEY, B.Sc., A.R.C.S., A.I.C.

Plate II

Introduction.—Rocks composed essentially of the mineral apatite are of extremely rare occurrence within the British Isles and the present example is, therefore, of considerable interest.

The rock was collected by Dr. J. E. Richey[1] during a rapid resurvey of the pre-Carboniferous formations adjoining the Sanquhar Coalfield, undertaken in order to complete one of the coalfield maps (Dumfriesshire 6 N.W.) for publication, and attention was first called to the abnormal apatite content by Messrs. Eckford and Mowbray Ritchie.

Field Relations.—The rock occurs in a volcanic vent of Ordovician (Caradoc) age which forms Bail Hill, 3 miles north-west of the town of Sanquhar. It is exposed in the bank about 80 yards from the mouth of a tiny stream which enters the Grain Burn 400 yards north-east of the point where the latter crosses the boundary fault separating the Carboniferous sediments from the ashes of the vent. The exposure may be more easily found by reference to a conspicuous outcrop of Ordovician chert, which forms part of a large inclusion in the vent. The apatite rock is situated 10 yards down stream from the termination of the chert inclusion against the vent-ash.

The rock forms a small, almost vertically disposed slab, from an inch or so to ten inches in width, which can be traced for a distance of a few yards. The slab is bounded by ash and appears to be a fragment of some larger rock-mass incorporated in the vent. At the outcrop it is weathered and porous, but fresh, dark-grey material was obtained by excavation.

The excavation showed that the slab of apatite rock came to an end at the top of the bank, and that its junction with the ash on either side was abrupt. The material is homogeneous throughout and a vein-like origin is exceedingly improbable. In this respect it is worthy of note that the adjacent rocks show no trace of scapolitic or other alteration due to vein solutions.

Petrography.—In hand specimen the apatite rock is a rather granular, fine-grained type not unlike a somewhat impure sandstone in its general appearance but readily distinguished by its higher specific gravity and by the presence of abundant, typical little prisms of yellowish apatite which are particularly

[1] The authors are indebted to Dr. Richey for details concerning the field occurrence of the rock described in the present paper.

conspicuous on weathered surfaces. When fresh the material is greyish in colour, dense and compact, but it assumes a brownish tinge and develops a porous structure due to weathering out of the calcareous base.

Under the microscope (30535; 30849-53; 31276-78)[1] the rock is found to consist almost entirely of tiny apatite prisms up to about 0.8 mm. in length but generally rather less than half this size. A fine-grained base of granular calcite is usually present, but it is not uniformly distributed throughout the rock and tends to occur in the form of small, sporadic, irregular patches. The only other constituents are sparse, scattered, formless grains of barytes and some shreds and irregular plates of dark mica,[2] together with an appreciable amount of magnetite and a little fine-grained quartz. In one or two slices a very subordinate amount of some finely-divided micaceous mineral was observed but could not be determined with precision.

The apatite is a fluorine-bearing type with the following optical constants :—

$$n_\omega = 1.637$$
$$n_\varepsilon = 1.634$$
$$n_\omega - n_\varepsilon = .003$$

In the carbonate-free varieties it forms an aggregate of small, euhedral prisms and grains with occasional larger individuals which produce a pseudo-porphyritic appearance. Associated with this aggregate are sparse crystals of barytes distinguished by their characteristic cleavages, moderate birefringence, optically positive character and small axial angle. The golden-brown, pleochroic phlogopite tends to build resorbed-looking wisps and shreds wedged between the apatite and appears to be of slightly earlier formation than the latter. Magnetite forms irregular blobs often enclosing fragments of apatite, and suggesting a replacement origin at some slightly later stage in the crystallization history of the rock. Quartz is of very restricted distribution and, when present, forms tiny mosaics occupying the interstices between the other minerals.

The carbonate patches distributed sporadically throughout the rock consist of fine-grained, granular mosaics of calcite in which are embedded prisms of apatite together with occasional grains of barytes, a few scraps of phlogopite and a little magnetite. All transitions may be seen between the calcite-rich and calcite-free varieties.

A typical specimen of the rock has been analysed and the result is set out below.

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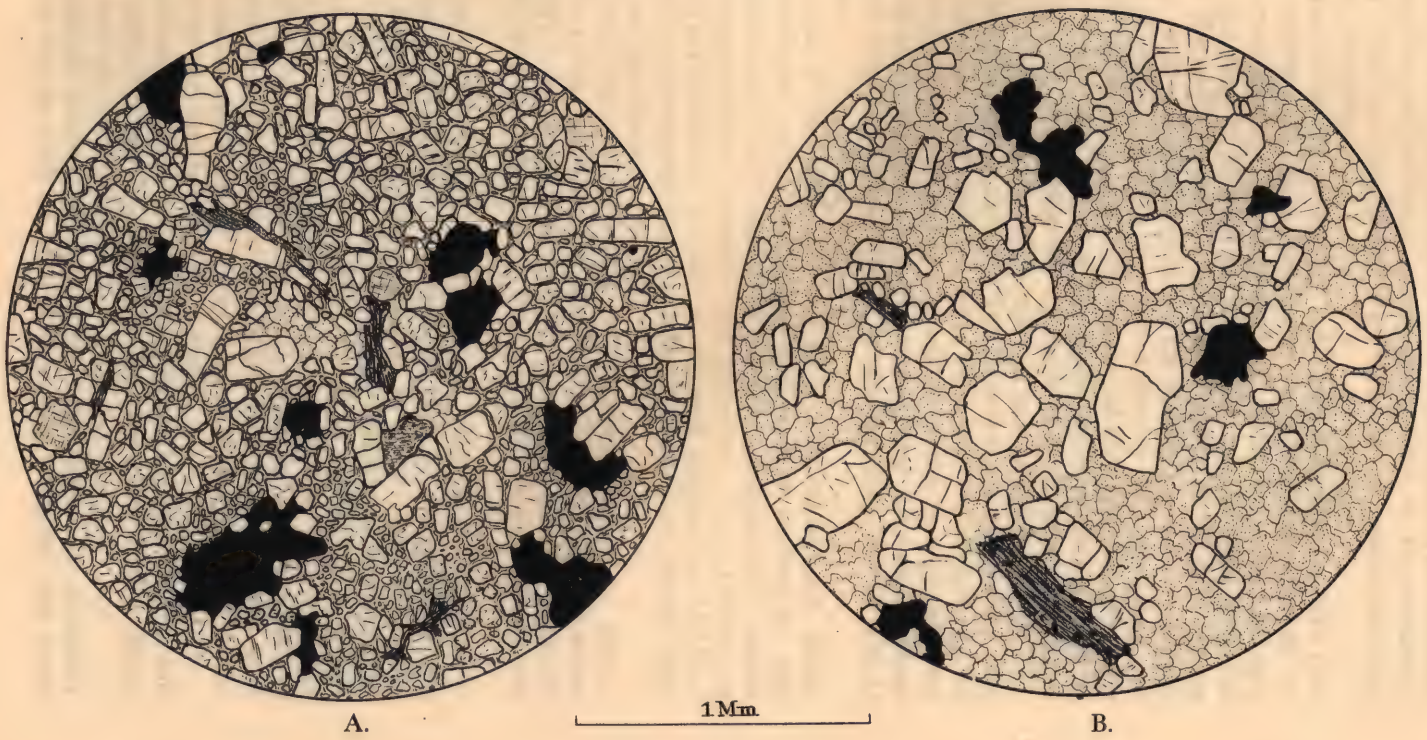
[1] These numbers refer to rock slices in the Survey Collection.

[2] It is seen from the chemical data set out on page 56 that all the FeO present in the rock is used up in the formation of magnetite and none is available to enter into silicates. The dark mica in question must therefore belong to the magnesia-rich type phlogopite.



APATITE ROCK FROM DUMFRIESSHIRE.

A. Predominant type composed of apatite, phlogopite, barytes and magnetite (little or no calcite).

B. Calcareous patch showing the relations of the minerals to the fine-grained calcite base.

Method of Analysis.—In a highly phosphatic and fluorine-bearing rock of this type certain analytical difficulties arise owing to the fact that the ordinary group separation of the metals is completely disorganized in the presence of a preponderating amount of phosphate.

The usual methods of dealing with this difficulty involve preliminary removal of the phosphate as phosphomolybdate or zirconium phosphate. Another method which involves adding a sufficient quantity of an iron or aluminium salt to deal with the phosphate (Lassieur, *Ann. Chim. Anal.*, 1934, *16*, p. 197) cannot be applied to highly phosphatic rocks, owing to the unmanageable bulk of the precipitate and the difficulty of obtaining an accurate figure for alumina. A scheme of analysis suited to the present rock and based on a preliminary removal of the lime as sulphate (Mellor, ' Treatise on Quantitative Inorganic Analysis ', 1913, p. 606) was therefore worked out as follows.

After destruction of silicates and removal of fluorides, the barium, strontium and calcium were removed as sulphates in aqueous alcoholic medium, and the metals of the iron group were precipitated as phosphates in acetic acid-acetate solution. Magnesium and traces of calcium were recovered from the filtrate as phosphates.

Separation of iron and titanium from aluminium and phosphate was effected by precipitations with sodium hydroxide, and the aluminium was finally separated from the phosphate by means of 8-hydroxyquinoline (Lundell and Knowles, *U.S. Bureau of Standards J. of Research, 3,* 1929, p. 91) and weighed as Al_2O_3.

Analysis by the method of a synthetic mixture of known composition gave satisfactory results.

Silica and Fluorine.—Neither the classical method of Berzelius, nor the recent method of Hoffman and Lundell (*U.S. Bureau of Standards J. of Research, 3,* 1929, p. 581) can be directly applied to the determination of fluorine and silica in phosphate rock.

Reynolds and Jacob (*Ind. Eng. Chem.* 1931, *3,* p. 366, Analytical Edition) have found that, unless special precautions are taken, the recovery of the fluorine may, in some cases, be as low as 50 per cent. of the true value. They describe a modification of Hoffman and Lundell's method which is applicable to phosphate rock, but which does not entirely eliminate the tendency of the result to be low. However, as the method of Reynolds and Jacob appeared to be the best available, it was used, with such modifications as would allow of the determination of silica in the residues from the fluorine determination.

The method involves removal of silica with zinc nitrate followed by ammoniacal zinc oxide, the fluorine being finally determined as lead chlorofluoride.

In a difficult analysis of this type, the order of accuracy attainable is not so high as in ordinary rock analysis, and some

of the figures, such as those for Al_2O_3 and Sio_2 should be regarded as approximations. The figure for fluorine is probably a little low.

APATITE ROCK FROM BAIL HILL, DUMFRIESSHIRE

SiO_2	8.8
Al_2O_3	1.1
Fe_2O_3	1.7
FeO	0.9
MgO	1.6
CaO	45.7
Na_2O	0.2
K_2O	0.1
TiO_2	0.4
P_2O_5	30.3
MnO	0.1
CO_2	3.7
SO_3	1.4
Cl	0.3
F	1.4
BaO	0.6
SrO	0.4
Loss on ign. less CO_2 ...	1.4
	100.1
Less O for Cl and F... ...	.7
Total	99.4

Analyst, C. O. Harvey.

Discussion of Analysis.—With the exception of apatite and phlogopite the minerals in this rock are of simple constitution and the approximate composition of the apatite can be derived by calculation. In making the calculation, however, certain assumptions are necessary. In the first place the position of the SrO is uncertain, and it may be present either as a sulphate, in solid solution with barytes (baryto-celestine), or as a constituent of the apatite. The former view has been adopted but, even on this assumption, more than half the total SO_3 remains after the equivalents have been allotted to BaO and SrO. This excess sulphate must be present in the apatite.

The FeO and Fe_2O_3 are completely used up in the formation of magnetite, indicating that the dark mica must be of phlogopitic nature, while the CO_2 goes to produce calcite. All the remaining CaO, SO_3, Cl, F and P_2O_5 must be present in the apatite and the residue represents quartz and phlogopite. The result of the calculation is as follows:—

	Calcite ...	8.40	
	Magnetite	2.55	
	$(BaSr)SO_4$	1.66	
Apatite	$Ca_3P_2O_8$	65.72	$3(Ca_3P_2O_8)CaF_2$ ... 52.0
	CaF_2 ...	2.89	$3(Ca_3P_2O_8)CaCl_2$ ... 5.5
	$CaCl_2$ ...	0.44	$3(Ca_3P_2O_8)CaSO_4$ ... 13.5
	$CaSO_4$ ...	1.36	$3(Ca_3P_2O_8)CaO$* ... 29
	CaO ...	2.50	
	Rest ...	13.80	
	Total ...	99.32	

It is evident, therefore, that the apatite from Bail Hill is not a pure fluorapatite but contains an appreciable admixture of the sulphatapatite ($3Ca_3P_2O_8,CaSO_4$) and carbonatapatite ($3Ca_3P_2O_8$. CaO) molecules, in which respect it is directly comparable with an apatite described by R. Brauns[1] from the Laacher See region. The optical similarity is also exceedingly close, as the following values show.

	Apatite from Bail Hill	Apatite from Laacher See
n_ω	1.637	1.6379
n_ε	1.634	1.6346
$n_\omega - n_\varepsilon$	.003	.0033

In the striking predominance of fluorine over chlorine the Dumfriesshire mineral resembles the apatites of the Canadian deposits,[2] in contrast to the chlorapatites of the Norwegian occurrences[3] and those recently described from Palabora in the Eastern Transvaal by Shand[4] and du Toit.[5]

Genesis of the Rock.—Apatite rocks of this general type have been described from many parts of the world and appear to result from a variety of causes.

The older views, in which they were regarded as metamorphosed organic deposits or as products of lateral secretion, are now only of historical interest, and it is unanimously admitted that they are intimately related to igneous activity. Here again, however, various interpretations have been advanced and the issue is confused by the fact that, undoubtedly, several dis-

* When the approximate constitution of the apatite is calculated as shown there remain an excess of 1.2 per cent. CaO in the amount (2.50 per cent.) given by calculation of the mode.

[1] Brauns, R., *N. Jahrb. Min.*, Beil. Bd., xli, 1917, pp. 84-86.

[2] Ossan, A., 'Notes on Certain Archaean Rocks of the Ottawa Valley,' *Geol. Surv. Canada, Ann. Rep.*, Vol. xii, 1899, p. 35 (o); H. S. Spence, 'Phosphate in Canada,' *Dept. Mines Canada*, Publ. No. 396, 1920.

[3] Vogt, J. H. L., *Zeit. prakt. Geol.*, 1895, pp. 367-370, 444-459, 465-470.

[4] Shand, S. J., 'The Granite-Syenite-Limestone Complex of Palabora, Eastern Transvaal, and the Associated Apatite Deposits,' *Trans. Geol. Soc. S. Africa*, Vol. xxxiv, 1931, pp. 81-105.

[5] du Toit, A. L., 'The Genesis of the Pyroxenite-Apatite Rocks of Palabora, Eastern Transvaal,' *loc. cit.*, 1931, pp. 107-127.

tinct genetical types exist. In some cases the rocks are believed to represent segregations from a molten magma while in others they are regarded as true veins, intimately related to the cassiterite-pneumatolytic types.[1] A study of the literature would appear to indicate that the majority of such apatite rocks result from the pneumatolytic-contact metamorphism or pyrometasomatism of limestones.

The presence of a calcareous base in the Bail Hill rock is weighty evidence against its being a magmatic segregation, nor can it be regarded as a vein in view of its relations to the enclosing rocks and the absence of scapolitic alteration in the latter. All the evidence, both field and microscopical, points to a metamorphic origin and there can be little doubt that it represents a pneumatolytically altered calcareous sediment.

At the same time it differs radically in certain respects from rocks of presumably similar origin in Canada and South Africa.[2] The latter occurrences are characterized by the association of apatite with diopside and other calc-silicates, which betray the metamorphic effect of the adjacent magma, and often become enriched to form ' secondary ' pyroxenites. In the case under discussion, however, the rock is almost devoid of silicates with the exception of a very subordinate quantity of phlogopite. It must be remembered, however, that the Dumfriesshire rock occurs, not at or near the contact of a limestone formation with a plutonic mass, but as an inclusion *in a volcanic vent.* The dissimilarities must, therefore, in the opinion of the writer, be ascribed to the natural physico-chemical differences between plutonic and volcanic conditions.

Apatite, almost certainly of secondary origin, occurs in abundance throughout the materials of the vent, and this suggests that the formation of the phosphate rock took place *in situ* and not at some remote source deep within the roots of the volcano. The alteration must have been effected through the medium of volcanic gases at relatively low temperature rather than by a fluid phase at high temperature. Confirmation of this view is also found in the presence of appreciable quantities of sulphate.

Du Toit[3] has pointed out that the conversion of calcium carbonate into apatite by the action of P_2O_5 is an *exothermic* reaction, while the formation of diopside, etc., is *endothermic.* Under conditions such as those prevailing in a volcanic vent, the formation of apatite by fumarolic action could proceed at temperatures which precluded the development of calc-silicates. It is to such gaseous emanations at relatively low temperature that is ascribed the formation of the apatite rock and, in this

[1] Niggli, P., ' Ore Deposits of Magmatic Origin,' London, 1929, p. 37.
[2] Spence, H. S., *op. cit.*, 1920, pp. 108-122.
[3] du Toit, A. L., *op. cit.*, 1931, pp. 107-127.

respect, it is not without significance that the sulphatapatites of the Laacher See region also formed as the result of pneumatolytic volcanic action.[1]

The presence of SO_3 in the emanations is highly significant for, although it is an exceedingly abundant constituent of fumarolic gases, it does not appear to exist among the volatile components emitted from a plutonic mass and fixed by the adjacent rocks. It is possible, therefore, that the presence of sulphatapatite may afford a criterion to distinguish deposits of volcanic-pneumatolytic origin, such as the Dumfriesshire occurrence, from those produced under plutonic conditions.

[1] Brauns, R., *op. cit.*, 1917, pp. 90-92.

IV.—SOME EXPOSURES OF CORALLIAN ROCKS NEAR CAMBRIDGE

BY

E. E. L. Dixon, B.Sc.

Text-figure 1.

THE following notes put on record exposures of the two most widespread subdivisions of the Corallian of the Cambridge district, *viz.*, the Elsworth Rock below and the Ampthill Clay above.

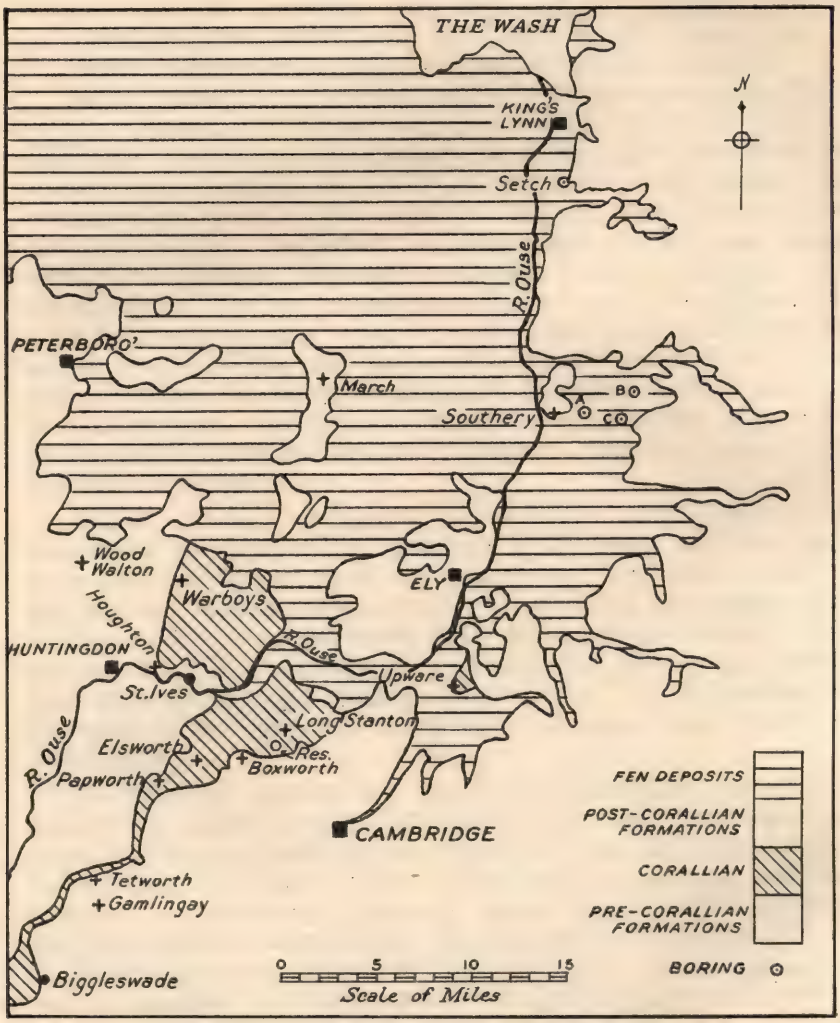


FIG. 1.—*Southern Part of the Fen Basin.*
Corallian Outcrops and the Positions of the West Norfolk Borings discussed on pp. 80-84

Since the work of Thomas Roberts[1] on the Jurassic rocks of that district and of C. B. Wedd[2] on the Corallian formations in particular, little fresh knowledge of the Ampthill Clay thereabouts has been obtained. In Roberts' time the clay was dug for bricks in many small pits. Now, with the pits disused and overgrown, it is difficult to bring our information up-to-date. The importance of the evidence that lies buried awaiting chance disclosure may be gauged from Dr. Arkell's discussion (pp. 64-80) of the bearing on classification of some fossils obtained in 1932. The fossils in question were found when a circular reservoir, 18 ft. in diameter, was sunk to a depth of about 25 ft. in the Ampthill Clay outcrop north-west of Cambridge. The site (Fig. 1)[3] is on the eastern bank of a small stream, 310 yds. east-north-east of Bar Farm, Long Stanton All Saints, and 5½ furlongs south-west of the church (N.S. 1 in. map, Sheet 187; 6 in., Cambs. 33 S.E.). We are indebted to the engineers, Messrs. G. W. Lack and Sons, for facilitating the examination. The beauty and abundance of the ammonites (see p. 65 *et seq.* and Pl. III) led to Mr. W. Dewar's co-operation in collecting the fossils and also in describing the section as the work progressed; the account of the section is based largely on his notes. The fossils have been named by Dr. W. J. Arkell.

Ampthill Clay, reservoir near Long Stanton, Cambridge

		Ft.
8.	Soil and Glacial gravel, fine, many small chalk-pebbles; thickness 2-7 ft., average	5
7.	Clay, light-grey or buff above, with stones near top, darker below, with impersistent layer of *Gryphaea*, some encrusted with *Serpula*, at 8 ft. from surface	5¾
6.	*Gryphaea*-bed, some of the shells *Serpula*-encrusted ...	¼
5.	Dark bluish clay with selenite and a few lines of nodules, to 9 in. diam., of pale grey, argillaceous limestone; frequent fossils, uncrushed ammonites to 4 in. diam. and large belemnites, the ammonites partly pyritised and some filled with pale limestone; phosphatised bone-fragment. *Grammatodon* or *Cucullaea*, *Gryphaea dilatata* J. Sow., *Thracia depressa* J. de C. Sow [common] and belemnite fragments [cf. *Oxyrrhynchus* Lhuyd]	3¾
4.	*Gryphaea*-bed, like bed 6	¼
3.	Dark-grey clay, with limestone-nodules like those in bed 5 and frequent fossils, the belemnites confined to the upper part and the ammonites preserved as in bed 5 but small. *Chlamys sp.*, *Gryphaea dilatata* J. Sow. [large, abundant], *Lima subantiquata*? Roemer ...	6½

[1] 'Jurassic Rocks of the Neighbourhood of Cambridge,' 1892.

[2] 'Corallian Rocks of Upware (Cambs.),' *Quart. Journ. Geol. Soc.*, vol. liv, 1898, pp. 601-19; and 'Corallian Rocks of St. Ives (Hunts.) and Elsworth,' *ibid.*, vol. lvii, 1901, pp. 73-83.

[3] The map merely shows the places mentioned in the text and a diagrammatic representation of the known Corallian outcrops, without prejudice to the questions of the western limit of the main outcrop or the existence of other outcrops in the 'islands' of the Fens, such as the March 'island.'

2.	Dark-grey clay with limestone-nodules; ammonites large (to 15 in. diam.), coarse-ribbed, uncrushed and filled with limestone; some ammonites and gryphaeas encrusted with *Serpula*, etc. *Grammatodon* or *Cucullaea*, *Gryphaea dilatata* and *Placunopsis* ? (Phill.) [attached to a *Gryphaea*]	2¼
1.	Grey clay with abundant fossils, including ammonites to 4 in. diam. and gastropods (*Alaria*?), also *Astarte sp.* [group of *A. cordata* Trautsch.], *Camptonectes lens* (J. Sow), *Exogyra nana* (J. Sow.) [common] and *E. nana* var. *praevirgula* Jourdy [one spec.], *Grammatodon* or *Cucullaea*, *Gryphaea* [young?] and *Thracia depressa*	¾
	Total depth	24½

The dip of the beds is low and, owing to the absence of well-defined bedding-planes, indeterminable. The general dip of the Ampthill Clay hereabouts is east-south-eastward but is apparently variable. Of the outcrop of the formation, which is situated in the almost featureless bottom of the Ouse Valley, the western boundary, that with the Elsworth Rock below, though traceable with precision, is several miles distant, and the eastern boundary, that with the Kimmeridge Clay, is vague in the extreme. Consequently the horizon of the Ampthill Clay at any spot, such as the Long Stanton reservoir, could be learnt only from palaeontological evidence were it not that the outcrop of the Boxworth Rock, a 2-3 ft. limestone in the middle of the formation, described by Seeley and Roberts, has proved to be at least locally mappable. From their relative position we find that the clays in the reservoir overlie the Boxworth Rock, a fact which is inferred also by Dr. Arkell from his examination of the ammonites.

Further, the lowest clays in the reservoir probably lie not far above the Boxworth Rock. At Boxworth the base of the Kimmeridge Clay appears, from measurements of heights of outcrops, to be at most 35 ft. above the Boxworth Rock, and at the reservoir it is certainly not represented in the 19 ft. or so of clay *in situ*. Hence, of the Ampthill Clay above the Boxworth Rock, there appears to be no more than 16 ft. to apportion between the beds below the reservoir section on the one hand and those above it on the other. The clays below the reservoir, Dr. Arkell suggests (pp. 76-7), may be on the horizon of those which contain the abundant *Amoeboceras* (*Prionodoceras*) *serratum* and *Perisphinctes variocostatus* found in Glacial Drifts. Those clays have nowhere been found in undisturbed sequence with other Corallian horizons.

The mapping of the Corallian is hard enough at the bottom of the Ouse Valley, but over the plateau to the north, between the Ouse and the Fens, the limits of the formation, owing to the covering of Boulder Clay, are practically unknown. Of the localities mentioned by Dr. Arkell (pp. 71-2) from which Corallian

fossils have been obtained, the most interesting is Warboys, where a large brick-pit in the high bank that looks northward over the Fens reveals a fine section[1] of Oxford Clay capped by a 4-6 ft. bed of clayey limestone. The latter, which had been mentioned by Whitaker, seemed to Mr. C. H. Dinham too thick to be a bed in the Oxford Clay and was consequently regarded by him as probably the local representative of the Elsworth Rock, and placed in the Corallian.[2] On examination it was found to be lithologically so unlike the Elsworth Rock all along the outcrop in the Ouse Valley to the south, from Houghton to Tetworth, that for a time the correlation was doubted. Some ammonites obtained from Warboys, however, have enabled Dr. Arkell (p. 71, footnote 2) to confirm Mr. Dinham's suggestion that the limestone-band is of Corallian (Upper Oxfordian) age.

Elsewhere along its outcrop the Elsworth Rock invariably includes masses of *Serpula* and *Exogyra nana*; in the Ouse Valley below Papworth ironshot grains also are a constant feature. The Warboys limestone is not ironshot, and, although *Serpula* encrusts many of the small lamellibranchs that are locally abundant in the upper part, and also occurs free, no large masses were found. One feature, however, was noticed connecting the bed with the Elsworth Rock elsewhere—parts of it contained frequent spines of sea-urchins.

[1] It is satisfactory that an adequate description of this important section has been undertaken by Mr. A. G. Brighton.

[2] On the Geological Survey map, 4 miles to 1 in., Sheet 16, ed. 2 (1933).

V. REPORT ON AMMONITES COLLECTED AT LONG STANTON, CAMBS., AND ON THE AGE OF THE AMPTHILL CLAY

BY

W. J. ARKELL, M.A., D.Sc., F.G.S.

Plates III, IV.

INTRODUCTION

THE specimens collected by Messrs. Dewar and Dixon from a casual opening in the Ampthill Clay at Long Stanton represent an assemblage of ammonites[1] hitherto unknown in this country, or in some instances known only by examples from the Glacial Drift. The species link up with elements in faunas known from Pomerania, the Moscow Basin and Greenland, and they enable the Ampthill Clay to be dated with greater precision than has been possible before.

I am indebted to the Director of H.M. Geological Survey for permission to study the specimens, and I also wish to acknowledge the valuable help received from Mr. A. G. Brighton, of the Sedgwick Museum.

DESCRIPTION OF THE MATERIAL

(a) STRATIGRAPHICAL DETAILS

The collection comprises:—

1. About 45 individuals and fragments of *Amoeboceras*, well preserved.
2. About 15 small fragments of various portions of medium-sized *Perisphinctes*, the shell mainly preserved.
3. About 12 more or less incomplete casts of body-chambers, some having a few septa and casts of gas-chambers attached, belonging to large Perisphinctids of a new genus named *Pomerania* below.
4. About 12 minute nuclei belonging mainly to a new genus described below as *Decipia*, all but one less than one inch in diameter, well preserved in pyrites.

The field-records show on analysis the following:—

All the large body-chambers and all the minute nuclei belonging to the two new genera came from Beds 1 and 2, at depths of 21½ ft. to 24½ ft.

[1] To be described and figured by the author in a monograph on the Ammonites of the English Corallian Beds in course of publication by the Palaeontographical Society.

About half the *Amoeboceras* and one minute nucleus of a tumid *Perisphinctes* (No. 54900) and one fragment of a medium-sized *Perisphinctes* (indet.) came from Bed 3, at depths of 15 ft. to 21½ ft.

About half the *Amoeboceras* and all except one of the fragments of medium-sized *Perisphinctes* came from Bed 5, at depths of 11 ft. to 14¾ ft.

From this analysis and from field evidence in the district, we can construct the following sequence :—

Upper Ampthill Clay (seen to 19½ ft.) :—

		Ft.
	Superficial deposits, to 5 ft., above	
6—7	Clay with no ammonites	6
4—5	Clay with *Amoeboceras* aff. *pseudocaelatum* Spath, *A.* (*Prionodoceras*) *truculentum* S. Buckman and *Perisphinctes spp.*	4
3	Clay with *Amoeboceras*, same species	6½
1—2	Clay with *Pomerania* and *Decipia, gen. nov.*	3
	Gap, unknown, perhaps 10 ft. or	? 20
Boxworth Rock		2—3
Lower Ampthill Clay	about	? 25
Elsworth Rock		
Oxford Clay		

It will be shown below that there is evidence of three zones in the Ampthill Clay, and I therefore subtract indefinite amounts from the Upper and Lower divisions of this sequence and group them together with the Boxworth Rock as the Middle Ampthill Clay.

(b) PALAEONTOLOGICAL DETAILS

Amoeboceras aff. *pseudocaelatum* Spath

Plate III, figs. 6-12

1904 *Cardioceras* cf. *alternans* Ilovaisky, p. 272, pl. xi, fig. 6 only. (*non* von Buch)

1935 *Amoeboceras* (*Prionodoceras*) aff. *pseudocaelatum* Spath, *nom. nov.*, p. 19, pl. ii, fig. 4.

Dr. Spath founded this species as *nom. nov.* for Ilovaisky's *C.* cf. *alternans* (*loc. cit.*, fig. 6 only). The type, according to Ilovaisky's figure, has the following dimensions :—Diameter 54mm., Whorl height 0.45, Umbilicus 0.24. At a diameter of 40 mm., which is more comparable with the Long Stanton material, the dimensions are the same except that the umbilicus is 0.23 and there are 31 primary ribs.

The most complete of the Long Stanton specimens (crushed, but with mouth-border and rostrum preserved) measures 42 mm., with whorl-height 0.42 and umbilicus 0.24, and there are likewise 31 primary ribs to the whorl.

Long Stanton yielded about 40 specimens assignable to this species, all from Beds 3 and 5. One block of clay measuring 5 x 3 cm. has remains of 7 specimens. Many are crushed, but a number have only the body-chamber crushed, while the septate inner whorls are in a beautiful though fragile whitish and iridescent

state of preservation. They agree with the inner whorls of Ilovaisky's figure except that lateral nodes are less definite. In this respect, therefore, they compare better with Dr. Spath's East Greenland specimen.

The material collected by Messrs. Dixon and Dewar at Long Stanton substantiates Dr. Spath's opinion that a wide variation must be allowed for, and justifies his referring to his material as an ' enodate variety.' In some the suggestion of nodes is stronger than in others. There is also much variation in the spacing of the ribs. In a specimen from Long Stanton (No. 54907 (3)) the ribs, both primaries and secondaries, are more widely spaced than in the others. But on the reverse side the ribbing is normal. This specimen has 29 secondary ribs per half whorl at 20 mm. on one side and 33 at the same diameter on the other.

Amoeboceras (*Prionodoceras*) *truculentum* S. Buckman

1927 *Prionodoceras truculentum* S. Buckman, pl. dcciv.

Three fragments from Bed 5, Nos. Dw. 2758, 2760-1, belong to a *Prionodoceras* of the group of *A.* (*P.*) *serratum* (J. Sowerby) (1813, p. 65, pl. xxiv). The first is a fragment representing rather less than a quarter whorl at about 50 mm. diameter. It shows six strong simple primary ribs, separated by regular short intercalatories. The second specimen is the first quarter of a body-chamber at a diameter of about 80-90 mm., and shows ribbing of the same type fading rapidly. The primary ribs are still strong, long and simple, and one or two are somewhat nodate. The third specimen is a quarter whorl at a slightly larger diameter just after the ribs have died out. In all three specimens the keel is rubbed off.

The nearest match with these specimens is *Prionodoceras truculentum* S. Buckman (1927, pl. dcciv). The primary ribs of the holotype are more numerous at corresponding diameters, but the ribbing is of the same strength and proportions, and the difference is probably of only varietal significance.

The ribbing is much coarser than and does not fade so early as in *A.* (*P.*) *serratum* (J. Sowerby) (*loc. cit.*). Both syntypes of that species, from the Drift of Suffolk, are lost. The upper figure if accurate represents a specimen which cannot readily be matched. The lower figure, which I designate as lectotype, represents the commonest *Prionodoceras* of the Drift and Ampthill Clay; it becomes smooth at a diameter of about 50 mm. The species has been thoroughly described and figured (as *Cardioceras serratum*) by Salfeld (1915, p. 172, pl. xviii). Other specimens, which may prove to belong to the same species, have been figured by Buckman

as *Prionodoceras prionodes* and *P. excentricum* (Buckman, 1920, pl. clv; and 1924, pl. cdlxiv).[1]

The specimen figured as *Am. serratus* by Damon from the *Trigonia clavellata* Beds (not Kimeridge[2] Clay) near Weymouth, and identified by Spath (1933, p. 863) as " a coarse variety of *Amoeboceras serratum* Sowerby sp." and as " a finely-ribbed variety of *A. truculentum* (Buckman) " (1933, p. 868) does not closely resemble either of these species. It is distinguished by its short primary ribs, its long and regular paired secondaries, rarity of either simple primaries or intercalatory secondaries, and absence of nodes on the secondaries.

Perisphinctes spp. [Fragments]

Most of the fragments of true *Perisphinctes* are too small for certain identification. They are well preserved, however, some with the shell perfect although fragile. They do not represent any of the numerous species of *Perisphinctes* found in the Berkshire Oolite Series or Osmington Oolite Series, with which close comparison has been made. Nor do they resemble any forms known in the English Kimeridge Clay.

Since by far the commonest Perisphinctid in the Drift of the Midland counties is *P. variocostatus* Buckland (= *P. biplex* J. Sowerby), a species which is always assumed to have been derived from the Ampthill Clay, it is surprising that the Long Stanton collection contains only two fragments closely comparable with this species (Nos. Dw. 2748-9). Even these cannot definitely be identified as such specifically, and they are in a different state of preservation from the familiar forms in the Drift.

Other fragments (Nos. Dw. 2750, 2752-3, 2757) are identical with the inner whorls of a species to be described elsewhere, so far known in the complete state only from the Drift of Bourne, Cambridgeshire (Sedgwick Mus. No. J. 3786), and from the Drift (?) of Lincolnshire (Day Coll., Geol. Surv. Mus., No. 58060, locality unknown) (both presumed to have been derived from Ampthill Clay). Fragments which appear to belong to the same species have been collected also in the Ampthill Clay (10 ft. below the Lower Greensand) in Gamlingay brickpit (Sedgwick Mus., No. 2679); in the Ampthill Clay (level unknown) of Ampthill railway cutting (Geol. Surv. Mus., No. JR. 3314); and in the Boxworth Rock (Sedgwick Mus., No. J. 389). It is a new species, not classifiable in any existing subgenus. The ribbing and whorl-

[1] Spath (1935, p. 24, footnote) seeks to restrict the name *serratum* to the upper of Sowerby's figures calling the common smooth form represented in the lower figure *prionodes* Buckman) and thereby virtually suppressing the name *serratum*, current for over a hundred years. He did not designate a lectotype. I consider the species *serratum* to have been fixed once and for all by Salfeld in his monograph, but I here designate Sowerby's lower figured specimen lectotype, and failing that Salfeld's specimen as neotype (Salfeld, 1915, pl. xviii, figs. 1a, 1b, 1c, Geol. Surv. Mus. No. 26059).

[2] The author has given reasons elsewhere (Arkell 1933, p. 441 footnote) for retaining the spelling, Kimeridge, the form originally adopted by the Ordnance Survey (O.S., Sheet 16, 1811); in accordance with its usual custom the Geological Survey has followed the spelling Kimmeridge, in use on the present Ordnance maps.

section closely resemble *Dichotomoceras dichotomum* S. Buckman, but the suspensive lobe of the suture is not so dwarfed and the ribs on the body-chamber modify differently towards the aperture.

Some of the fragments from Long Stanton showing no body-chamber or suture may possibly belong to *Dichotomoceras dichotomum,* and others (e.g., No. Dw. 2751) suggest by their ribbing the subgenus *Biplices* (*sensu stricto*). Lastly, there is a tiny nucleus of a tumid biplicate Perisphinctid with deep constrictions, too small for identification (Plate III, fig. 5).

It will be seen that these Perisphinctids are of little help in correlating, since they belong to species known only from either the Drift or isolated exposures of Ampthill Clay themselves imperfectly dated.

Perisphinctid Nuclei

Decipia gen. nov., Pl. III, figs. 1-4

The majority of the tiny nuclei from Beds 1 and 2 are assigned to a new genus *Decipia,* to be described elsewhere, the type being *Ammonites decipiens* J. Sowerby. This species represents a genus distinct from *Perisphinctes* and its many subgenera, and perhaps as worthy of full generic separation as *Pictonia* or *Ringsteadia,* to which it seems to be closely allied.

The largest of the Long Stanton nuclei (Geol. Surv. Mus., No. 54897) (Pl. III, fig. 2) measures 27 mm. in diameter, and it overlaps by a few mm. with the smallest visible part of the smallest undoubted *Decipia decipiens* that I have been able to obtain—a specimen from the Ampthill Clay of North Kelsey, Lincolnshire (Sedgwick Mus., No. J. 2664). It is not identical specifically, the ribbing of the Long Stanton nucleus being finer and the whorl less compressed; but the style of ribbing is essentially similar. From a diameter of about 20 mm. onwards the ribs bifurcate fairly regularly at a low angle, with regular intercalatories, and the secondaries pass quite strongly over the venter with only a gentle forward sweep.

At diameters less than about 20 mm. in all the specimens (the best are Nos. 54896-9, *see* Pl. III figs. 1-4) the ribbing, from the point where it first begins to be discernible (about 9-12 mm.) up to about 20 mm., is regularly triplicate in distinctly dischizotomous sheaves. In some of the specimens the sheaves are almost rectiradiate, or may branch slightly forward, in others they branch backward, and the direction is backward in all of them at the earliest stage. Some specimens show regular intercalatories, others only a few. Constrictions are more marked than at later stages (as in *D. decipiens*), and number about three per whorl. The secondaries are wholly concealed by the overlapping whorls, none being visible in the umbilicus.

At first sight these small nuclei recall the Lower Kimeridgian Rasenids, especially the genus *Prorasenia,* but comparison with a

series of different species of *Prorasenia* from the Rasenia and Pictonia Zones of Stratton, Hatton and Abbotsbury, shows that they are not congeneric or even closely related. They differ from *Prorasenia* in having much finer ribbing, which becomes finer and smoother instead of coarser and sharper as growth proceeds, in possessing longer primary ribs (the secondaries are nearly always visible in the umbilicus of *Prorasenia*), and in displaying constrictions and numerous intercalatories. In the genus *Prorasenioides* Schindewolf the primaries are still shorter and the ribbing is more flexiradiate.

In the other Rasenid genera, *Rasenia, Involuticeras, Rasenioides* and *Pararasenia*[1] the triplicate and dischizotomous ribbing is not confined to the earliest whorls but persists much later, and so comparisons are still less close.

Apart from the rest of the fauna, therefore, it can confidently be stated that these nuclei are not Rasenids and that a Kimeridgian age need not be postulated for them. They may possibly be nuclei of the large body chambers found in the same beds, but against this must be set the facts that they are differently preserved and that no specimens of intermediate sizes were found to connect them.

Perisphinctid Body-Chambers

Pomerania gen. nov.[2]

The twelve large body-chambers and parts of body-chambers, with a few gas-chambers attached to some of them, constitute perhaps the most interesting part of the assemblage. They belong to a new genus, resembling *Decipia* in some respects. I propose for it the name *Pomerania* gen. nov., with genotype *P. dohmi,* n.n. for " *Pictonia* " *baylei* Dohm (1925, p. 32, pl. v, fig. 6) from the Ringsteadia Zone of Zarnglaff in Pomerania.

The identifiable Long Stanton material belongs to three species.[3] One may be conspecific with *P. robusta* Dohm 1925, p. 32, pl. vii, fig. 3) and another is comparable with *P. latecosta* Dohm (1925, p. 32, pl. ix, fig. 6, and pl. iv, fig. 2; non *latecostata* Törnquist, 1896), both from the Ringsteadia Beds of Zarnglaff. The characteristic features of this genus are the *Perisphinctes* suture, the large size, and the ontogeny of the ribbing, which is believed to be like that of *Decipia* on the inner whorls, but fades on the middle whorls, and then strengthens to large swollen ridges and wedges on the outer whorl—both the later formed gas-chambers and the body-chamber.

It has been pointed out previously (Arkell, 1935a, p. 247) that, contrary to what has been said by Dohm and Spath (1933, p. 867),[4]

[1] *See* Arkell, 1935a, p. 252.
[2] Too large to be figured except on quarto plates.
[3] Some of the pieces are too fragmentary to be worth discussion.
[4] Dr. Spath has since admitted that Dohm's fossils are not the Kimeridgian *Pictoniae* (Spath, 1935, p. 42).

these giant Perisphinctids with coarse-ribbed outer whorls cannot be congeneric with *Pictonia*, as understood by Bayle, Salfeld, or any previous author, and that they represent a distinct genus not yet known from strata so high as the Pictonia Zone (basal Kimeridge). They are, in fact, characteristic of the Ringsteadia Zone of the uppermost Oxfordian in Pomerania, and the Long Stanton specimens, together with another mentioned below, confirm this dating.

Correlation and Dating

(a) *Amoeboceras pseudocaelatum*

At the type-localities, Miatschkowo and Novoselski in Western Russia, *Amoeboceras pseudocaelatum* is confined to Ilovaisky's Bed D, where it is abundant. Bed D consists mainly of shaly clay and is about 6 metres thick at Miatschkowo. Unfortunately little else occurs with it that gives any clue to correlations, the only other characteristic ammonite being a small Cardiocerate which Ilovaisky calls *C. cordatum* var. B (1904, pl. x, fig. 30). From the small fragment figured it is not possible to identify this with certainty, but it suggests part of a nucleus of the enodate variety of *A. pseudocaelatum*. Bed D, however, overlies strata (Beds A and B, together about $3\frac{1}{2}$ metres thick), which contain Cardiocerates characteristic of the Transversarius Zone: *C. cordatum* auct., *C. excavatum, C. goliathum, C. vertebrale,* etc., together with large Perisphinctids (rare) identified as *P. martelli*. In between comes only 0.7 metre of clay with ' *C. cordatum* var. B ' and *C. zieteni* Rouiller (Bed C).

At Cape Leslie in East Greenland Spath records *A. pseudocaelatum* "several metres below the Pecten Sandstone, Neoxfordian (Upper Argovian-Rauracian), *transversarius* or *bimammatum* zones." From the Pecten Sandstone he records *A. alternoides* (Nik.), and from 11 metres above its base another *Prionodoceras* which he identifies as aff. *superstes* (Phillips). Buckman (1923, pl. cdxxii has figured *A. superstes* from the Brill Serpulite Bed, which is believed to be on the borderline between Upper Calcareous Grit and Kimeridge Clay, and Spath (1935, p. 23) records *A. alternoides* in the Ampthill Clay.

In England, " an evolute variety of *pseudocaelatum,* without lateral nodes and therefore showing resemblance to the form figured in de Loriol's fig. 10," is said by Spath (1935, p. 20) to have been collected by Blake from the Upper Calcareous Grit of Nunnington, Yorkshire, and recorded by him as *Amm. alternans* = *serratus*.

Hence, on the evidence of this Amoebocerate we can date the clay at Long Stanton as of Bimammatum Zone age and in N.W. European chronology post-Plicatilis Zone and therefore somewhere

in either the *Perisphinctes variocostatus* or the *Ringsteadia pseudocordata* Zone.[1]

(b) *Amoeboceras truculentum*

The holotype of *A.* (*P.*) *truculentum* S. Buckman came from Wood Walton railway cutting, six miles N.N.W. of Huntingdon (map, Fig. 1, p. 60), from clay which H. B. Woodward described as Oxford Clay and Buckman as Kimeridge Clay. From the same cutting came the holotype of *A.* (*P.*) *excentricum* S. Buckman (1924, pl. cdlxiv), and a large and typical specimen of *Perisphinctes variocostatus* (Buckland) (Geol. Surv. Mus. No. 48499).[2]

The holotype of *Prionodoceras excentricum* S. Buckman, which was found associated with *P. truculentum* at Walton cutting, is probably conspecific with *A.* (*P.*) *serratum* of J. Sowerby and of Salfeld, a species more widely distributed, both in the Drift and *in situ*. The latter species was collected by Salfeld *in situ* in clay formerly exposed at Telford Road claypit, Swindon, and with it he found what he identified as *Perisphinctes decipiens* (J. Sowerby) (Salfeld, 1914, p. 196, and 1915, p. 174). Although Buckman subsequently assumed the acme of *Prionodoceras spp.* to have been attained after the *Ringsteadia* hemera, Salfeld in 1914 considered the clay with *P. serratum* at Telford Road to lie *below* the band of ironshot oolite with *Ringsteadiae*; in other words, that it was Upper Oxfordian (Corallian) and not Kimeridgian.

A single specimen probably referable to *P. serratum* but more discoidal is known from the ironshot oolite itself, in the same matrix as the *Ringsteadiae*, from Stratton railway cutting, near Swindon (Taunton Museum, Tomkins Coll., No. 3666). The commoner *Prionodoceras* from that bed, however, is the smaller, still more discoidal, and more coarsely-ribbed *A.* (*P.*) *marstonense* Spath (1935, pl. iv, fig. 5; and Oxford University and Taunton Museums), which is not known from Ampthill Clay.

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[1] Since this was written Dr. J. Pringle has kindly put at my disposal the cores from the borings at Southery, Norfolk, described by him (1923, pp. 129-30). He allows me to say that in my opinion the ammonites referred to by him as *Cardioceras sp.* on p. 130 are *Amoeboceras* aff. *pseudocaelatum*. The specimens are marked as coming from depths of 283 and 290 ft. in the Severals Ho. boring (C). Forty feet higher come 20 ft. of clays with abundant *Raseniae* (depths 208-228 ft.). The *Amoeboceras* from 247 ft. seems to indicate basal Kimeridge Clay, and the *Cardioceras* from 268½ ft. is a *Prionodoceras* (probably Corallian). *See* later, p. 83, 'The Ampthill Clay in some Norfolk Borings.'

[2] If the clay in which these fossils were found was in place, it must have been Ampthill Clay; but it seems to me more likely to have been Drift. Wood Walton is well out in the outcrop of the Oxford Clay according to the Geological Survey Map (Sheet 16, colour printed 1-inch, 1909). It lies six miles west of the nearest known occurrence of Corallian clays, at Warboys brickyard (where an argillaceous limestone at the top of the pit and underlying a few feet of clay has yielded Corallian—Berkshire Oolite—Perisphinctids to Mr. Brighton, Mr. Dixon and myself) and at Fenton (*see* Roberts, 1892, p. 47). It is not impossible, however, that the outcrop of the Elsworth Rock does not turn northwards under the Drift near Houghton Hall, east of Huntingdon, as Wedd supposed (1901, p. 80), but continues farther west along the left bank of the Ouse, just under the Drift. My attention is drawn by Mr. C. H. Dinham to a note to the effect that "Corallian fragments" were observed on a small isolated hill standing north of the main high ground 1,800 yards W.N.W. of Great Raveley Manor House (about midway between Wood Walton and Warboys). *See* the library copy of the Geological Survey map, 6″ to mile, Sheet Hunts. 14 N.W. A third possibility is that at Wood Walton some Ampthill Clay is let down by a fault belonging to the same system as the fault which brings up the inlier of Cornbrash between Yaxley and Stilton, six miles to the north-west.

Again, there are fragments of *Prionodoceras* which appear to be *P. serratum* or a near form in the Sandsfoot Grits of Weymouth, where they are associated with *Ringsteadiae* but are below the acme of that genus, which is reached in the overlying ironstone band (= Ringstead Coral Bed) and Ringstead Waxy Clay (Arkell, 1933, pp. 385-6).[1] Salfeld also recorded *P. serratum* from the Sandsfoot Grits.

A fragmentary young specimen less than 20 mm. in diameter from the Boxworth Rock is preserved in the Sedgwick Museum (No. J. 386), but it can only be identified specifically with the greatest hesitation as *A.* (*P.*) *serratum*.

It is tantalising that at the only place where *A.* (*P.*) *serratum* and *Perisphinctes variocostatus* (Buckland) have been found together in a Jurassic clay the clay had been transported by ice. The erratic was pierced by a well 2 miles S.S.E. of Biggleswade Station, Bedfordshire, and was 67 ft. thick, with 8½ ft. of boulder clay above and 16½ ft. below, the whole resting on undisturbed but eroded Gault (Home, 1903). The ammonites from the 67 ft. of Jurassic clay were identified by E. T. Newton as *Cardioceras excavatus* (J. Sowerby) and *Perisphinctes variocostatus* (Buckland) and on this evidence the clay was considered to be Ampthill Clay by Messrs. Newton, Kitchin and H. B. Woodward, though W. H. Hudleston thought the erratic might have come from the Lower Kimeridge. Some of the ammonites are preserved in the Sedgwick Museum, Cambridge, and they can be identified with certainty as fragments of *Perisphinctes variocostatus* (Buckland) (typical; Nos. J. 3788-9, 2687) and well preserved complete specimens of *Amoeboceras* (*Prionodoceras*) *serratum* (J. Sowerby) (Nos. J. 3790-1), with fragments of young specimens exactly like that figured by Salfeld, 1915, pl. xviii, fig. 1a, 1b (No. J. 3795-7) and several others ribbed to a rather later stage (J. 3793-4). They are all in the state of preservation typical of those in the Drift, and this large erratic undoubtedly came from the horizon from which the numerous well-preserved Drift specimens were derived.

(c) *The Perisphinctids*

The Perisphinctids give us corroborative and more precise information. Little can be inferred from the tiny nuclei or from the fragments of *Perisphinctes*, for they all belong to species which, with the exceptions mentioned, are known exclusively from the Drift.

The large body-chambers of *Pomerania*, on the other hand, can be dated with precision. They are closely comparable, in two instances perhaps specifically identical, with forms figured by Dohm (1925) from beds yielding abundant *Ringsteadiae* at

[1] The only fragments known to me from this locality are unfortunately worn and devoid of the keel, having been picked up by me from the beach at Wyke Regis, but they are in unmistakable red grit matrix.

Zarnglaff in Pomerania. Dohm's ammonites have also been identified in association with *Ringsteadiae* in Swabia (Beurlen, 1926, p. 89). (Cf. *Am. gigantoplex* and *ptychodes* Quenstedt).

Confirmation of this dating comes from Wiltshire in a single well-preserved specimen of the same genus discovered about a century ago in the Westbury Ironstone of Stratton railway-cutting, near Swindon (Tomkins Coll., Taunton Museum, No. 3670). From the same cuttings (or borrow-pits?) at Stratton and Marston, came numerous *Ringsteadiae,* and the Amoeboceratesjust discussed. All the ammonites are in the same argillaceous ironshot matrix as that in which the *Ringsteadiae* occur at the top of the Upper Calcareous Grit at Weymouth.

As recently pointed out (Arkell 1935a, pp. 248-9), the ironshot bed underlies the basal Kimeridge Clay with numerous *Pictonia* and *Prorasenia,* which is dug close to the railway cutting at Stratton brickyard (Messrs. Iles and Sons). In November, 1935, I learnt that a hole had been dug 9 ft. below the bottom of the pit, and that nothing but clays with layers of *Ostrea delta* had been encountered (evidently still *Pictonia baylei* Zone). Close below must lie the ironshot oolite encountered in the adjacent cutting, and we know from borings at Swindon and Red Down, Highworth (Arkell, 1933, p. 395) that this is separated by 21½ ft. of clay from the Coral Rag.[1]

With these borings to give us the thicknesses, we can now piece together the following lithological and palaeontological succession for the Swindon district:—

	Ft.	In.
KIMERIDGE CLAY (penetrated to 42′ at Swindon; *see* Chatwin and Pringle, 1922, p. 164).		
Bluish-grey clay in boring	21	0
Bluish-grey clay in Iles' brickyard with *Pictonia spp.* and *Prorasenia spp.*, and *Ostrea delta*, seen to about... ...	12	0
Clay with layers of *Ostrea delta*, at least	9	0
Seam of pale grey shelly limestone with *O. delta*		1
CORALLIAN BEDS		
Ironshot oolite band, grey and brown, earthy, with many *Ringsteadia spp.*, also *Pomerania sp. nov.*, *Amoeboceras marstonense* Spath, *A. serratum* (J. Sowerby) (1 specimen), and *Camptonectes sandsfootensis* Arkell (2 giant double-valved examples at Oxford and Taunton Museums). Formerly seen in railway cuttings... ... 6 inches to	1	0
Clay, the upper 2 ft. hard, brown, calcareous and muddy in Swindon boring, and much of it red and sandy at Red Down. *Amoeboceras serratum* (J. Sowerby) and *Decipia sp.* (?) recorded by Salfeld at Telford Road old claypit, Swindon, in upper part (presumably); passes into red and yellow sands at Shrivenham	21	6
Coral Rag, limestones, etc., below.		

Another species that seems to belong to the genus *Pomerania* occurs at Le Havre: *Ammonites berryeri* Lesueur (Dollfus,

[1] Contrary to what I wrote in 1927, p. 151, when I under-estimated the dip of the Coral Rag below Stratton brickyard.

1863, pp. 15, 42 pl. iv). Dollfus recorded it from the " Marnes à Ptérocères " (in the form of a cast, as figured). The record is vague, for Dollfus included in this rock-group not only the restricted " Calcaire marneaux à Ptérocères " of Lennier's record (Douvillé, 1881, p. 450, bed h), only 3 ft. thick, from which were obtained most of the *Pictoniae* and *Raseniae* figured by Törnquist (1896), but also an unknown proportion of the 40 ft. of marls and other rocks below, above his next-lowest rock-group, the " Calcaires à Trigonies ". (Dollfus, p. 4, and Douvillé, 1881, p. 450, beds a-g). Tornquist (1896, pl. viii) figured an ammonite under the name *Olcostephanus berryeri* (Dollfus), from the restricted Pteroceras limestone (bed h of the section), but the ammonite is a Rasenid and quite different from Dollfus' original. If this was the closest match that Törnquist could find among the material from the *Pictonia* and *R. cymodoce* bed, there is reason for inferring that the original *Am. berryeri* of Dollfus did not come from that horizon but from some lower part of the 40 ft. of beds called Marnes à Ptérocères by Dollfus. These beds, at least up to Lennier's bed f, correlate bed for bed with the Marnes et Argiles de Villerville, and so thence with the Sandsfoot Grit and Sandsfoot Clay, according to H. Douvillé (1881, p. 452). Salfeld (1914, p. 212) recorded *Ringsteadia frequens* from some part of them at Villerville, and the occurrence there of ironshot oolite in bed f suggests the Ringstead Coral Bed at Weymouth and the same horizon in Wiltshire. In my opinion the vague " Calcaires et argiles à Trigonies " at Cap de la Hève, to judge by their lamellibranch fauna, are considerably higher than the *Trigonia clavellata* Beds, probably at least as high as the Sandsfoot Grits, as Waagen believed in 1865. They are less likely to correspond with part of the Sandsfoot Clay, of which the fauna in England is poor and little known. The only ammonites recorded from the Calcaires à Trigonies at Le Havre are " *Am. cymodoce* d'Orb." and " *Am. erinus*? d'Orb.", which in the terminology of 1863 may conceal *Ringsteadiae*. *A. cymodoce* also appears in Douvillé's record against Bed b, where it is probably a *Ringsteadia*.

Thus the evidence on the whole favours the supposition that the true *Am. berryeri* Dollfus occurs at Le Havre on about the same horizon as its congeners in England and Pomerania; namely in the Zone of *Ringsteadia pseudocordata*.

It seems probable that Salfeld recorded members of the genus *Pomerania* in various places as *Perisphinctes achilles* d'Orb., as did also H. Douvillé in 1881, and that this led to *P. achilles* being used by those authors as a zonal index for part of the uppermost Oxfordian strata now under discussion (Salfeld, 1914, Table I). In Swabia, however, the form referred to *P. achilles* seems to occur below the horizon with *Ringsteadia* and *Pomerania*, although still in the Bimammatum Zone. (*See* Beurlen, 1926, pp. 88-9). The precise nature of the original *P.*

achilles of d'Orbigny is doubtful, and it seems more likely to have been a Lower Kimeridge form (Tenuilobatus Zone).[1]

Conclusions as to the Zonal Range of the Ampthill Clay.

In 1927, S. S. Buckman (1927, vol. vi, p. 49) and the writer (1927, p. 153) simultaneously and independently published the opinion that the bulk of the Ampthill Clay occupied a higher stratigraphical position than had usually been supposed. Buckman, basing his opinion on the occurrence of *Perisphinctes variocostatus* (Buckland) and his new genus *Prionodoceras*, declared that the Ampthill Clay was of Lower Kimeridgian age. My conclusion was based on some small fragments of Perisphinctids collected by Prof. A. Morley Davies from a rock band about 20 ft. above the base of the Ampthill Clay, in a railway-cutting between Ashendon Junction and Rushbeds Wood Tunnel, Bucks. These fragments indicated a higher horizon than was represented in any of the normal Corallian Beds in Oxfordshire and Berkshire, and I concluded that the rock band, which suggested the Boxworth Rock, "tells us definitely, I think, that we have here an horizon probably equivalent to some part of the *Trigonia clavellata* beds of Dorset" (Arkell 1927, p. 153).

The section of the cutting examined by Prof. Morley Davies was as follows (much condensed):—

		Ft.
Ampthill Clay		
7.	Pale grey clay with small selenite crystals	30
6.	Stone band with Perisphinctids, less than	1
3-5.	Clay, with three unfossiliferous 9-inch stone bands ...	19
		50
Oakley Beds		
2.	*Exogyra nana* Beds; clays, marls, marly limestone full of *E. nana* and many other fossils, including *Perisphinctes spp.*	6 to 10 ft. or more
Oxford Clay		
1.	Clay, with many large *Gryphaea dilatata* and Cardiocerates "of *praecordatum* and *tenuicostatum* types" [*Cardioceras costellatum* Buckman?]	

I pointed out in 1927 that it was the *Exogyra nana* Beds (2) (= Buckman's Oakley Clay near Brill) alone that contained the Perisphinctids and lamellibranchs of the Upper Corallian (Plicatilis Zone) of the Oxford district; and that as these beds apparently pass eastwards into the Elsworth Rock they should not be included in the Ampthill Clay, which appears to be mainly of later date (*see* also Arkell, 1933, pp. 410-412). I except the lowest layers of the Ampthill Clay, for instance the lowest 18 ft. above the Serpulite Bed, as exposed at Gamlingay (*see* Fearn-

[1] Dr. J. Cottreau has kindly searched for types on my behalf in Paris but was unable to find any. It remains for a French author to work out the species and figure neotypes.

sides, 1904, p. 15, and Roberts, 1892, pp. 37-40), which have yielded *Cardioceras* and *Cawtoniceras spp.*, comparable with forms found in the Berkshire Oolite Series of the Oxford district and Yorkshire. Plicatilis-Zone clay has also been exposed at Swavesey, Cambs. (lowest 23 ft., *see* Roberts, 1892, p. 46).

It is now possible to say that at least one of the commonest ammonites of the Dorset *Trigonia clavellata* Beds, a new species to be described elsewhere, occurs in the Boxworth Rock of Boxworth (Sedgwick Mus., nos. J. 387, J. 385; and Geol. Surv. Mus., nos. 103, 104 C.B.W.). Another Dorset species is represented from the Ampthill Clay of Lincolnshire (*P. boweni* Arkell, 1935, p. 16; Brit. Mus.) and this probably comes from about the same horizon, because another Lincolnshire species (undescribed) in the same state of preservation, is among the few ammonites known from the Boxworth Rock (Sedgwick Mus., No. J. 389). In Dorset the position of these species is at the top of the *Trigonia clavellata* Beds, in the Red Beds, close to the junction with the Sandsfoot Clay. Now Roberts considered the Boxworth Rock in his area to lie at least 20 ft. above the base of the Ampthill Clay, and at Swavesey, if present at all, it must be more than 23 ft. above the base, according to his records, since it was not encountered in a well that struck Elsworth Rock at that depth. Hence we can say that about the lowest 25 ft. of the Ampthill Clay may bring us up to the horizon of the base of the Sandsfoot Clay (*see* Arkell, 1935, pp. 5-7).

It is noteworthy that, among the many ammonites from Long Stanton, there are only two fragments identifiable with *Perisphinctes variocostatus* (Buckland) (= *biplex* J. Sowerby) and no signs of *Amoeboceras* (*Prionodoceras*) *serratum* (J. Sowerby). Yet these are by far the commonest ammonites yielded by the Drift, supposedly derived from the Ampthill Clay. Since the Ampthill Clay at Long Stanton is definitely above the horizon of the Boxworth Rock, the absence there of the common *P. variocostatus* and *A.* (*P.*) *serratum* may be explained by inferring that the principal source of these species is a lower horizon in the clay, either close above or below the Boxworth Rock; *i.e.*, Middle Ampthill Clay. If they came from above the clays exposed at Long Stanton, they would be as much Lower Kimeridgian, as Buckman thought, as Oxfordian. But it has been shown that the Boxworth Rock contains some ammonites from the Red Beds at the top of the Dorset *Trigonia clavellata* Beds. Neither the true *A.* (*Prionodoceras*) *serratum* nor the true *Perisphinctes variocostatus* is known from the Dorset Red Beds, but they have yielded a specimen of *Prionodoceras* (*Am. serratus* Damon) which was considered a variety of *A.* (*P.*) *serratum* by Damon and by Spath (though I regard it as a different species), and they also contain what are undoubtedly the nearest allies of *P. variocostatus* and *P. strumatum*, namely *P. cautisnigrae* Arkell and *P. uptonensis* Arkell (1935, pp. 10, 14, plates i, ii, iii, vii).

Hence, on the evidence available, it may be inferred that the main source of *P. variocostatus* and perhaps also *A.* (*P.*) *serratum* is below the clays exposed at Long Stanton and probably close to the horizon of the Boxworth Rock. At present, there is no satisfactory index for this important ammonite zone, which probably represents approximately the South-West German and Portuguese Tiziani Zone of Siemiradzki (1898). *P. variocostatus* being so common and characteristic in this country, I propose tentatively to adopt it as zonal index for the Middle Ampthill Clay and Dorset Trigonia Beds. It was figured by Buckland in 1836, in the sixth Bridgwater Treatise, and was chosen by Hudleston as a Characteristic Fossil for his " Supracoralline group " in 1878 (table facing p. 410). It should be clearly understood, however, that the placing of this zone below instead of above that of *Ringsteadia pseudocordata* is still only tentative, for correlation with the Boxworth Rock and thence with the Dorset Trigonia Beds is not altogether satisfactory.

From what has been stated, it is evident that the Upper Ampthill Clay of Long Stanton belongs to the Ringsteadia Zone, the highest zone of the Upper Oxfordian (Corallian) Beds, and so may be correlated with the Upper Calcareous Grit of other counties. *Ringsteadia* itself was not found at Long Stanton; it seems to be absent from the whole Ampthill Clay area, and is unknown from the Drift. This is remarkable in view of its abundance in Dorset, Pomerania and Normandy and its extension to Swabia; even more remarkable than the absence of *Perisphinctes variocostatus* from Dorset or Yorkshire.

Comparison with Upware

Roberts (1892, p. 8) after successfully refuting Seeley's opinion that the Ampthill Clay was older than the Coralline Oolite of Upware and that the Elsworth and St. Ives Rocks occupied different horizons in the Oxford Clay, summarised his knowledge of the correlation of these strata by means of the following table :—

		Upware Section
4.	Kimeridge Clay	
3.	Ampthill Clay	Coral Rag Coralline Oolite
2.	Lower Calcareous Grit (Elsworth and St. Ives Rocks)	
1.	Oxford Clay	

In the ten years that followed, much new light was thrown on the succession at Upware. The three most important discoveries were the following. (1) Keeping showed that the Kimeridge Clay rests with signs of erosion directly on the Coral Rag, in an exposure no longer visible. (2) Wedd showed that the Elsworth Rock does indeed underlie the Corallian Rocks at Upware, as Roberts had supposed, but had been unable to prove. (3) Fearnsides, by

excavations in the floor of the South Pit, and Wedd, by excavations near by, proved that a lower coral rag is developed in the Coralline Oolite below the South Pit, and that this lower coral rag rests directly on the Elsworth Rock (*see* Rastall, 1909, and Fearnsides, 1904).

Palaeontologically, the greatest advance was made by Wedd, who, in the course of his detailed mapping of the Elsworth and St. Ives Rock, found *Perisphinctes " plicatilis "* abundantly in the rock at three places, Papworth Everard, north of St. Ives, and north-east of St. Ives. He " dwelt upon the great abundance of ammonites of the *plicatilis* type in the Elsworth and St. Ives Rock" (Wedd, 1901, p. 85), and this abundance led him to infer that the Rock was of Upper Corallian date instead of Lower Calcareous Grit. Examination of the ammonites and other fossils from the Rock in the Sedgwick Museum has enabled Dr. Spath and the writer independently to confirm Wedd's dating. The majority of the fauna, in fact, indicates the Berkshire Oolite Series of the Oxford district, namely the lower part of the Plicatilis Zone (Spath, 1933, p. 866; Arkell, 1933, p. 413). Spath's conclusion that the Coralline Oolite (with its lower coral rag) cannot be distinguished zonally from the Elsworth Rock is in agreement with my own conclusion that in the south of England, and particularly the Oxford district, one zone suffices for the Berkshire and Osmington Oolite Series (Arkell, 1933, p. 376). This zone, the Martelli and Antecedens Zones of Salfeld,[1] should properly be called the Plicatilis Zone (having been first so called by Hudleston, 1878, *loc. cit.*).

I have on several occasions pointed out that the Coralline Oolite of Upware, with its lower coral rag, corresponds palaeontologically, lithologically and stratigraphically with the Osmington Oolite Series of the South of England (which contains the Coral Rag in the Oxford district); and that since the Coral Rag of Upware rests upon it and contains a number of special lamellibranchs not found in the Osmington Oolite Series, the Coral Rag of Upware is probably later in date than the Osmington Oolite Series; and further, that it may be correlated with the later coral reef of Steeple Ashton, Wilts., which occupies a similar position and seems to pass laterally into the *Trigonia clavellata* Beds of Dorset. If this correlation is correct, then the Coral Rag of Upware passes laterally into the Middle Ampthill Clay, including the Boxworth Rock, which we have seen yields some of the ammonites of the *T. clavellata* Beds, and which I place tentatively in the Zone of *Perisphinctus variocostatus* (old ' *decipiens* ' or ' *serratus* ' zone).

This correlation leaves the upper and thickest portion of the Ampthill Clay, with the Long Stanton ammonite fauna (Ring-

[1] Salfeld wrongly placed the Dorset Trigonia Beds in his *P. antecedens* Zone, for they are higher. *P. antecedens* is common in the Berkshire Oolite Series and ranges up into the Osmington Oolites.

steadia Zone), apparently unrepresented in the Corallian rocks of Upware.

The observation of Keeping, that Kimeridge Clay rests directly on the Coral Rag with signs of erosion, indicates that the Ringsteadia Zone is unrepresented at Upware. A similar non-sequence occurs in the Oxford district, but is of greater extent, for the Variocostatus Zone is absent also.

I would therefore amend Roberts' table as follows :— (the wider correlation now suggested is shown in the table on p. 80).

Oxford	*Ampthill Clay Area*	*Upware*
Absent	Upper Ampthill Clay	Absent
Absent	Boxworth Rock & Middle Ampthill Clay	Coral Rag
Osmington Oolite Series (with Coral Rag)	Lower Ampthill Clay	Coralline Oolite and lower coral rag
Berkshire Oolite Series	Elsworth Rock (with *Exogyra nana* Beds)	Elsworth Rock
Lower Calcareous Grit	Absent	Absent

[TABLE

CORRELATION TABLE

ZONES	CAMBRIDGESHIRE	BUCKINGHAMSHIRE	OXON	N. WILTSHIRE	DORSET
Ringsteadia pseudocordata	Upper Ampthill Clay with *Pomerania spp. Amoeboceras pseudocaelatum, A. truculentum.*	Brill Serpulite Bed, 1 ft., and Upper Ampthill Clay.	Absent	Ironstone band, 1 ft. of Swindon and Marston, with *Ringsteadia spp. Pomerania sp.* and *Amoeboceras marstonense.*	Ironstone band with *Ringsteadia spp.*, passing to Coral Bed, Ringstead Waxy Clay (12 ft.), Sandsfoot Grits (30 ft.) with *Ringsteadia*, Sandsfoot Clay (40 ft.), *Trigonia clavellata* Beds (25 ft.) with *Per. osmingtonensis* and other spp.
Perisphinctes variocostatus(?)	Boxworth Rock, 2-3 feet, and Middle Ampthill Clay, with *Amoeboceras serratum, Per. variocostatus* and *P. osmingtonensis* (=Upware Rag?)	Boxworth Rock, 1 ft. with *Perisphinctes* cf. *wartae* and Middle Ampthill Clay.	Absent	Clay (21 ft.) with *Amoeboceras serratum* near top at Swindon. Absent ? (pars)	
Perisphinctes plicatilis	Lower Ampthill Clay (Gamlingay, etc.) = Upware Coralline Oolite with few ammonites, Elsworth Rock with many ammonites of *plicatilis* zone	Lower Ampthill Clay and *Exogyra nana* Beds (= Oakley Beds) with Perisphinctids of *plicatilis* zone.	Osmington Oolite Series 30-65 ft. with few, and Berkshire Oolite Series up to 60 ft., with many ammonites of the *plicatilis* zone.		
Aspidoceras catena	Absent	Absent	Lower Calcareous Grit (at least upper part).		

THE AMPTHILL CLAY IN SOME NORFOLK BORINGS

Light is thrown on some of the problems discussed above by the borings in the Norfolk fens near Southery, described by Dr. J. Pringle in 1923. The position of these borings (map, Fig. 1, p. 60) is only 22-24 miles north-east of the last surface exposures of the Corallian clays at Fenton and Warboys brickyards. At my request Dr. Pringle has allowed me to work through the core-samples from the Upper Jurassic clays penetrated in these borings and some others (unpublished) farther north, near King's Lynn, and in addition he has put at my disposal his manuscript notes and has given me every facility. For this kindness I wish to express my sincere thanks.

Every specimen from the cores has the depth clearly marked on it at the time of collecting and all are preserved in their order of sequence. Re-examination of the fossils is therefore an easy matter.

The results, which are summarized in the accompanying sections (Pl. IV), confirm Dr. Pringle's conclusions (Pringle, 1923), with some modification due to later work, and at the same time reveal some of the Long Stanton fauna in sequence with the rest of the Oxfordian-Kimeridgian succession.

The principal limestone bands, which are shown in the sections, are those in the published descriptions, and the columns A, B, C correspond with the three borings already so styled. Only the minimum number of fossils has been entered, for the sake of clarity.

As was shown before, the Lower Greensand rests unconformably on the Kimeridge Clay from a few inches (at A) to 17 ft. (at C) above a seam of oil-shale, the equivalent of the Blackstone of Clavell's Hard, Kimeridge, Dorset; and both in this seam in all three borings and in the Blackstone at Kimeridge Dr. Pringle discovered plates of the pelagic Crinoid, *Saccocoma*. He showed that this fossil has a vertical range of less than 1 ft. in the Norfolk borings and 13 ft. in Dorset. It therefore provides an invaluable datum in correlating, and indicates that approximately the lower half only of the Kimeridge Clay is present in South-west Norfolk. This conclusion the ammonites corroborate abundantly.

Below the *Saccocoma* band, in the lower part of the Kimeridge Clay, are two other prominent palaeontological datum lines. About 50 ft. below *Saccocoma* the bedding planes of the shale are covered with *Amoeboceras krausei* (Salfeld), which occurs at Ringstead Bay in the Pseudomutabilis Zone (Salfeld, 1915, p. 201, pl. xx, figs. 6-10). At a level about 50 ft. lower is a mass of small fine-ribbed Rasenids, likewise flattened in the bedding planes, and with them are numerous coarse-ribbed Astartids usually identified as *Astarte mysis* d'Orbigny (*A. extensa* Phillips?). This is an unmistakable horizon and may be matched in the Mutabilis Zone of Ringstead Bay and elsewhere.[1]

[1] I am inclined to agree with Beurlen (1926, pp. 115-16) in suppressing the Yo Zone of Salfeld as merely a Teilzone of the Mutabilis Zone. The index fossil has never been found in Britain, and in Swabia it is found in the Rasenia Zones.

Dr. Pringle identified the Rasenids on this horizon as "*Involuticeras desmonotus* (Oppel) and allied forms" (1923, p. 135). In the absence of any monograph on the family, precise identification of Rasenids is difficult, and I hesitate to put any specific names to these small forms for the present. *Ammonites desmonotus* Oppel has since been made genotype of *Aulacostephanoides* Schindewolf, which Spath claims is a synonym of *Pararasenia* Spath, and as I have pointed out recently (1935a), since the genotype of *Aulacostephanus* is *Ammonites mutabilis* J. de C. Sowerby, if Spath is right both genera are strictly speaking synonyms of *Aulacostephanus* Sutner and Pompeckj.

Since the specimens are crushed I have not been able to determine whether the ribs pass over the venter as in *Amm. involutus* Quenstedt, the genotype of *Involuticeras* Salfeld, or whether they are interrupted by a narrow ventral smooth band as in *Amm. desmonotus* Oppel, the genotype of *Aulacostephanoides,* and in *Amm. striolaris* Quenstedt, the genotype of *Rasenioides* Schindewolf. I am inclined to agree with Schindewolf in not attaching generic or subgeneric importance to this feature and to regard it as a character likely to appear in some of the species of any lineage. This character apart, it seems that these Norfolk forms cannot be identified with *Amm. desmonotus* Oppel because they are more evolute and the primary ribs are more prominent. A closer comparison is with *Amm. striolaris* Quenstedt (1887-8, pl. cxxiv, fig. 8), a species said to come from the White Jura delta, which Roll equates with the Pseudomutabilis Zone. Pending monographic treatment of the Rasenids, therefore, it seems best to identify these forms as *Rasenioides spp.* (*Amm. striolaris* Quenst. being the genotype). If the venter proves to be wholly ribbed, then a better comparison will be with *Rasenia lepidula* (Oppel).

In boring B, *Rasenioides* occurred 11 ft. below this level and a fragment of a coarsely ribbed body chamber, probably belonging to a large Rasenid, at 23 ft. below it. In boring C a Rasenid occurred at 12 ft. and a smooth septate whorl-fragment which might belong to either a *Pictonia* or a *Rasenia* of the *cymodoce* group at 14 ft. below this same level. In Setch boring (unpublished), in which the *Rasenioides* level can also be recognized, a well-preserved specimen of *Rasenia involuta* Salfeld occurred 6 ft. below it and a *Rasenia* cf. *uralensis* (d'Orbigny) 36 ft. below it. So much therefore certainly belongs to the Zones of *Rasenia mutabilis, Rasenia cymodoce* and *Pictonia baylei* and is still Kimeridgian. Downwards there seems to be an imperceptible lithological passage into the Corallian (Upper Oxfordian), and it is noteworthy that no signs were found of layers of *Ostrea delta* or a phosphate bed, such as occurs in Cambridgeshire at the junction. Palaeontologically we must place the junction at Setch, and therefore probably also at Southery, at least 36 ft. (say 38-40 ft.) below the *Rasenioides* level; *i.e.,* at depths of about 210 ft. in boring B, 250 ft. in boring C, and

290 ft. at Setch. This is in each case about 22 ft. lower than is proposed in Dr. Pringle's published accounts.

The next fossils in descending sequence are highly interesting, but being for the most part large shells they are tantalisingly incomplete owing to the small diameter of the core. Reckoning from the arbitrary but uniform base of the Kimeridge proposed above, we may recognize fragments of medium-sized to large *Amoeboceras* (*Prionodoceras*) at the following depths: at 2 ft. in boring B; 1 ft., 18 ft., and 25 ft. in boring C; and 25 ft. at Setch. Most of these cannot be identified specifically, but one or two are certainly *Prionodoceras* near to, if not identical with, *P. serratum* (J. Sowerby), and the others are in harmony with this identification. It is interesting to find them here concentrated in the highest 25 ft. of the Ampthill Clay. On the other hand they are more crushed than the beautiful specimens so common in the Drift, and no trace of *Perisphinctes variocostatus* or other Perisphinctids was found. It is, therefore, still uncertain what level yields the Drift fossils discussed above.

The remaining Corallian clays yielded fossils only in boring C. At 33 ft. and 40 ft. below the base of the Kimeridge Clay (*i.e.*, at depths of 283 ft. and 290 ft.), were obtained well-preserved specimens of *Amoeboceras* aff. *pseudocaelatum*, unmistakably the same forms as those from Long Stanton described above. These fossils are marked as from levels which would fall below the base of the Ampthill Clay according to Dr. Pringle's grouping (1923, pp. 128, 130), which therefore stands in need of revision. A more satisfactory base for the Corallian occurs 30 ft. lower, below the 2 ft. of limestone at 320-322 ft. in boring C, which expands to 3 ft. 9 in. in boring B (289 ft.-292 ft. 9in.). I know of no limestone of this thickness in the Oxford Clay, but it may correspond with the limestone near the top of the pit at Warboys brickyard near Huntingdon, which, as mentioned above, has yielded Perisphinctids of the Plicatilis Zone.

The only objection to this readjustment is the entry "*Quenstedtoceras sp.* at 270½ ft." in the published account of boring B (1923, p. 128). But there is no specimen from anywhere near this level preserved in the core-samples; and Dr. Pringle, who has also kindly looked for it, agrees that there must have been a mistake in a field identification.

At a level about 28-33 ft. below the limestone in both borings are abundant pyritized specimens of *Quenstedtoceras scarburgense* (Young and Bird), which abounds at Warboys brickyard and indicates the Mariae Zone. The same species was also obtained abundantly from the Upper Oxford Clay at St. Ives and at Fen Stanton brewery boring (Wedd, 1901). Wedd recorded them as *C. cordatus*, but his specimens are in the Geological Survey Museum and are undoubtedly *Q. scarburgense*. With them he found *Q. mariae*. It appears, in fact, that the true Cordatus (Cardia)

Zone is absent from Cambridgeshire, or if present is unfossiliferous and reduced in thickness, for the Plicatilis Zone seems to rest on the Mariae Zone in all these sections.[1]

The Kosmocerates from lower down in the Oxford Clay cannot be identified with the same degree of certainty. Since Dr. Pringle described the borings many Kosmocerates have been figured by S. S. Buckman and we have the advantage of Brinkmann's monographs. In the light of this new information I do not think the Kosmocerates from boring B at levels only 35-70 ft. below the *scarburgense* level represent the early forms recorded in the published section from those levels and again from 30 to 50 ft. lower in boring C. Only one specimen from boring B (360 ft.) is in my opinion identifiable, and that seems to resemble *K. phaeinum* S. Buckman, which Brinkmann includes in *K. proniae* Teisseyre, a species commonest in the Athleta Zone (as at Wolvercote, Oxford). Three specimens from 458 ft. and 470 ft. in boring C seem to be best identifiable with *K. grossouvrei* R. Douvillé (*cf. K. zugium* S. Buckman). A smaller one from a foot lower may possibly be *K. jason*. These come from less than 10 ft. above the Cornbrash in boring C, but *K. grossouvrei* is by no means a basal Oxford Clay form—Brinkmann calls it " Upper Middle Callovian " and states that it spans the Castor and Pollux (Reginaldi) and Duncani Zones. Much of the basal Oxford Clay is therefore missing as well as the Kellaway Beds.

The total thicknesses of the formations according to this regrouping are as follows:—

	Feet	
	Boring B.	Boring C.
Kimeridge Clay (lower half only) ...	143	147
Corallian clays and limestone	83	72
Oxford Clay	106+	158

The considerable thickness of the Corallian clays appears to be due mainly to expansion of the uppermost zones. In view of the occurrence of *Amoeboceras* aff. *pseudocaelatum* in these clays both in Norfolk and at Long Stanton, it seems necessary to assign at least 40 ft. of the highest of the Corallian clays of Norfolk to the Zone of *Ringsteadia pseudocordata*. The *Amoeboceras* is not, however, necessarily on exactly the same level at the two places. Further, the abundance of shells of *Prionodoceras*, some at least of which are near to *P. serratum*, in this highest 40 ft. suggests equivalence with the clay seen by Salfeld at Telford Road, Swindon, which he placed *below* the Zone of *Ringsteadia pseudocordata*, the horizon of the Long Stanton clays. Nevertheless, on consideration of all the evidence available, the view is at present favoured that this part of the Norfolk Clays is referable to the *Ringsteadia* Zone, giving the latter a greater thickness in Norfolk than at any other place in this country.

[1] My own examination of the Warboys pit, however, has been far too superficial to establish this point firmly. Detailed work on this fine section by a geologist who can visit it frequently would yield valuable results.

No less remarkable is the thinness of the Oxford Clay, of which the top and bottom portions appear to be missing.

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Photos by W. J. A.

AMPTHILL CLAY AMMONITES
FROM LONG STANTON, CAMBRIDGESHIRE.

Description of Plate III

Ammonites from Long Stanton, Cambridgeshire

1. *Decipia sp.*, nucleus. No. 54896 Bed 2.
2. ,, ,, ,, No. 54897 ,,
3. ,, ,, ,, No. 54898 ,,
4. ,, ,, ,, No. 54899 Bed 1.
5. *Perisphinctes sp.*, nucleus. No. 54900 Bed 3.
6. *Amoeboceras* aff. *pseudocaelatum* Spath. No. 54901 Bed 3.
7. ,, ,, ,, ,, No. 54902 ,,
8. ,, ,, ,, ,, No. 54903 ,,
9. ,, ,, ,, ,, No. 54904 ,,
10. ,, ,, ,, ,, No. 54905 Bed 5.
11. ,, ,, ,, ,, No. 54906 (4) ,,
12. ,, ,, ,, ,, No. 54907 (3) ,,

All photographs natural size, from specimens in the Geological Survey collection.

Explanation of Plate IV

Sections through the Kimeridgian, Corallian, and Oxfordian Rocks in some West Norfolk Borings

Setch. Boring near West Winch, 3½ miles S. of King's Lynn. Height about 10 ft. O.D.

A. Boring at Decoy Farm, about 1¾ miles E. of Southery. Height about 5 ft. O.D.

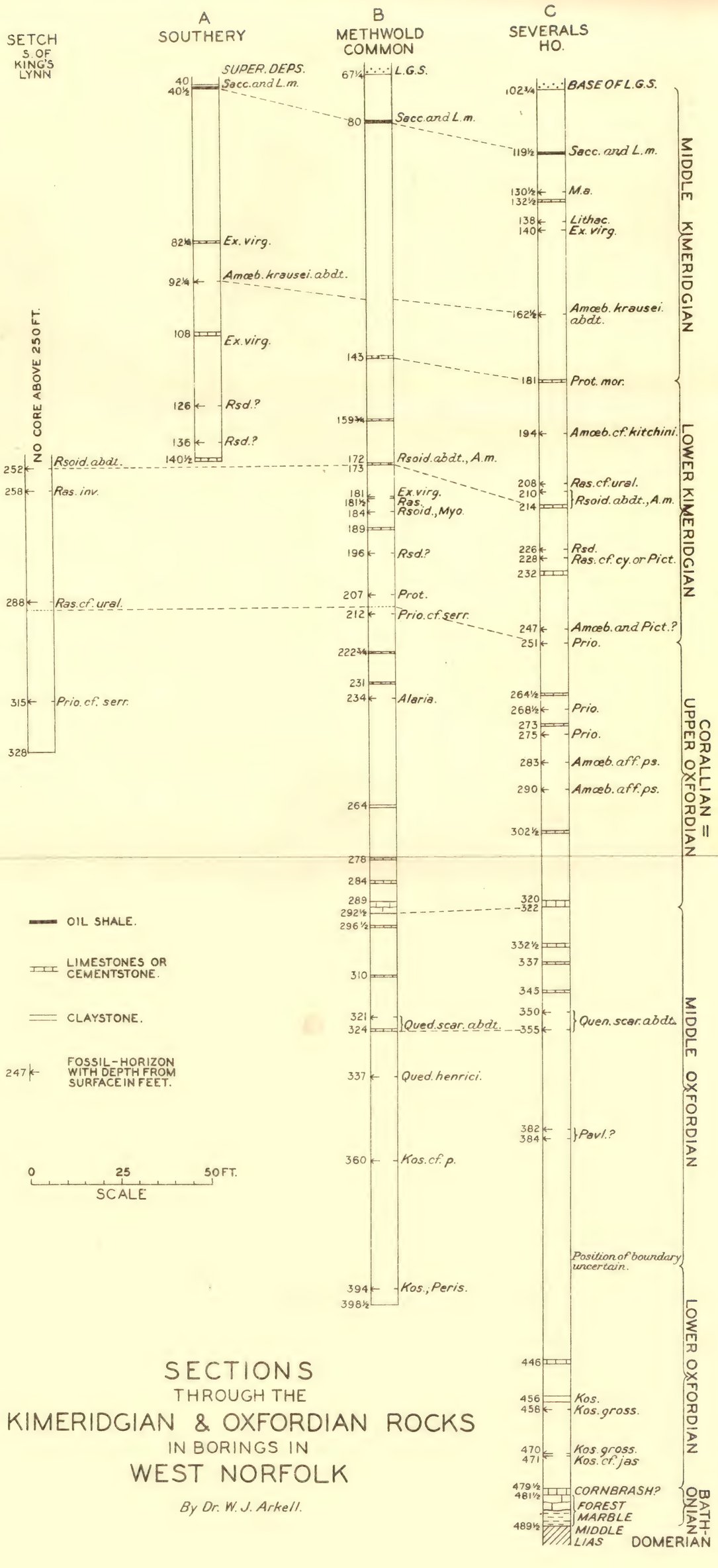
B. Boring on Methwold Common, about 3½ miles E. of Southery. Height 7 ft. O.D.

C. Boring, 1 mile N.E. of Severals Ho., 4½ miles E.N.E. of Southery. Height about 10 ft. O.D.

The Kimeridgian, Corallian and Oxfordian strata are clays or shales, with beds of oil-shale, limestone (or cementstone) and claystone at the horizons indicated on the sections.

Abbreviations

Abdt.	Abundant
Amoeb.	Amoeboceras
,, *aff.* ps.	,, *aff.* pseudocaelatum
A.m.	Astarte mysis
Ex. virg.	Exogyra virgula
Kos.	Kosmoceras
,, gross.	,, grossouvrei
,, *cf.* jas.	,, *cf.* jason
,, *cf.* p.	,, *cf.* proniae (*cf.* phaeinum)
L.G.S.	Lower Greensand
Lithac.	Lithacoceras
L.m.	Lucina minuscula
M.a.	Modiola autissiodorensis
Myo.	Myopholas
Pavl.	Pavloviceras
Prot.	Protocardia
,, mor.	,, morinica
Peris.	Perisphinctid
Pict.	Pictonia
Prio.	Prionodoceras
,, *cf.* serr.	,, *cf.* serratum
Quen.	Quenstedtoceras
,, scar.	,, scarburgense
Ras.	Rasenia
,, *cf.* cy.	,, *cf.* cymodoce
,, involuta	,, involuta
,, *cf.* ural.	,, *cf.* uralensis
Rsd.	Rasenid
Rsoid.	Rasenioides
Sacc.	Saccocoma
SUPER. DEPS.	Superficial Deposits



SECTIONS
THROUGH THE
KIMERIDGIAN & OXFORDIAN ROCKS
IN BORINGS IN
WEST NORFOLK

By Dr. W. J. Arkell.

VI.—A NEW SPECIES OF *TAXOCRINUS* FROM THE DELABOLE SLATES OF CORNWALL

BY

JAMES WRIGHT, F.R.S.E., F.G.S.

Plate V; Text-figure 1.

THE neat little crinoid which is the subject of this note was found in the quarry of the Old Delabole Slate Company Ltd. at Delabole, North Cornwall (one-inch Sheet 336) and was presented by Mr. J. Setchell, the General Manager of that firm, to the Geological Survey and Museum, where it is now registered as No. 54423. The counterpart of the specimen was given by Mr. Setchell to the Museum of the Cornish Geological Society, Penzance. I understand this is the only crinoid which has ever been found in the Upper Devonian at Delabole. The specimen is preserved in iron pyrites and consists of a somewhat crushed crown with a considerable part of the column in position. When first received, both crown and column were embedded in and much obscured by the slate, and I spent many hours in removing this matrix. The task, however, was a pleasant one, and I thank Dr. J. Pringle for the privilege of studying the specimen and for allowing me to use my own discretion in developing it.

FLEXIBILIA Zittel.
TAXOCRINIDAE Wachsmuth, *emend.* Springer.
Taxocrinus Phillips.
Taxocrinus delabolei sp. nov.

Description.—A small species; crown elongate, moderately expanding in lower part; arms long, tapering, with three bifurcations; calyx with broad base, slightly tapering sides; anal tube long, of at least 9 plates; no iBr; IBr 3; IIBr 5; IIIBr 6 to 11 (right ramus of left posterior ray 6 : 10; right and left rami of right posterior ray 11 : 7 and 7 : 10); IVBr 16 or more; column not expanding proximally, composed of moderately thick columnals with rounded margins, fairly uniform throughout; full length of crown, 33 mm.; length of column, 78 mm.

Remarks.—Flexible crinoids are rare in the English Upper Devonian rocks, and as a rule are poorly preserved. The specimen under discussion is perhaps in a better condition than most examples, especially as to the arm structure, which is beautifully shown in the left and right posterior rays. One could wish, however, that the crown had been less disturbed, since both these rays are slightly out of place in their lower parts and the cup lies at a slight angle to the top of column. The base of the cup is considerably obscured by pyrites, and no trace of infra-basals is seen. The

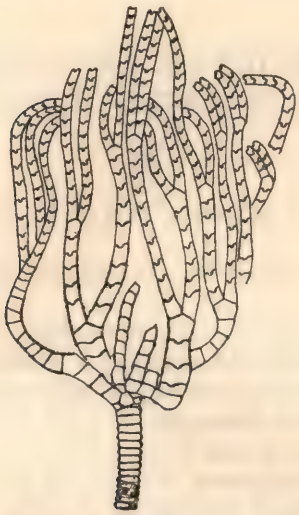


FIG. 1. *Taxocrinus delabolei* sp. nov. showing left and right posterior rays, anal tube, etc. x 1½.

other plates of the cup are also difficult to detect. I have tried to plot them in the drawing (Text-fig. 1), but the posterior basal is probably larger than it is shown there. The primibrachs number three. In the right posterior ray the primibrachs are turned over and lie with the grooved ventral surfaces upwards, at right angles to the secundibrachs of the left ramus, only four of these plates being seen. The lower part of this ray has been shifted to the right. The lower part of the right ramus of the left posterior ray has also been shifted to the right and inwards and only three of the IIBr are visible, the others being lost or buried in the matrix. Five appears to be the usual number of IIBr. This is indicated in the right ramus of right posterior ray where five can be counted. The IVBr give off no branches and taper very little throughout. They are still broad at their extremities so that the arms were probably much longer than are now shown in the specimen. The column is fairly uniform in width, tapering only slightly towards the distal end. It does not swell out near the cup as so often happens in Flexibilia. Owing to its pyritous and somewhat abraded nature, other details are difficult to elucidate. In the proximal region, and for some distance down, the columnals are comparatively easy to see, but in the median and distal regions the suture lines can only be detected with difficulty and under certain conditions of light and shade. Where distinctly seen, the columnals are moderately thick with rounded margins and they appear to have the same character throughout showing few variations of diameter or thickness. Proximally, however, next to the cup, the first four are thicker than the average and very prominent. They are possibly also slightly wider than those below, but it is difficult to judge accurately, since

1

2

J. Wright Photo

Taxocrinus delabolei sp. nov. from Upper Devonian, Delabole, North Cornwall.
Geol. Survey Coll., No. 54423.
Fig. 1, the complete specimen, Nat. Size.
Fig. 2, the crown ×2.

this part of the column seems rather more squeezed and is abraded slightly on the right side. I cannot see any trace of thin columnals immediately below the cup.

From the number of primibrachs and other characters, there seems little doubt that the specimen is a *Taxocrinus*. This genus is represented in the Devonian of Europe and America by comparatively few species. Of these, *T. macrodactylus* (Phillips) and *T. stultus* Whidborne occur in the Pilton Beds (Upper Devonian or Lower Carboniferous) of North Devon. It is clear that the Cornish specimen does not belong to the former species since, among other details, it is much smaller and has a column quite different in character and does not expand at the top as in *T. macrodactylus*. As to *T. stultus*, there is more agreement, and on the available evidence I am inclined to think that *T. delabolei* is more closely related to that species than to any other. At the same time, there is no doubt that it also comes close to *T. telleri* Springer, from the Middle Devonian of Wisconsin, U.S.A. (Springer, pl. 52, figs. 7-8). The number of IIBr in both is five and the arms bifurcate much in the same way, the outer divisions being longer than the inner. In *T. telleri*, however, the IIBr number 7 or 8 to 14 against our 6 or 7 to 11. The American crinoid is, however, a larger species with a few interbrachials of which there are no signs in the Cornish specimen. It is probably also less spreading in the lower part of the crown and the cup appears to be relatively broader. Further comparison cannot be made as the column is not known.

Comparison with *T. stultus* is hampered by the poor state of preservation of the figured specimens (Whidborne, pl. 34, figs. 1-3; Springer, pl. 51, figs. 5 a-c). It has to be noted that these specimens only show the proximal region of column and lower part of the crown. Nothing is known of the arms beyond a few tertibrachs, although Whidborne says:—" Upper series of brachials indistinctly seen in the specimens, but possibly short and few and inclined to curve inwards ". (*Op. cit.*, p. 216). One must make allowance for the condition of the specimens, but if this statement is correct, the Cornish specimen differs from *T. stultus* in these characters, the arms being long and tapering. In the lower part of the crown the specimen from Delabole agrees fairly well with *T. stultus*, the cup being about the same size as the smaller of the two figured specimens, but as far as one can judge from the figures the secundibrachs in *T. delabolei* are much wider. Another noticeable feature is that the Cornish example, allowing for its being somewhat flattened, appears to have a greater spread from the cup upwards. This may be inferred from the slope of the primibrachs and secundibrachs in the left ramus of the left posterior ray, together with what may be considered as the primibrachs of the right anterior lateral ray, now seen between the right ramus of the right posterior ray and the anal tube (Plate V, Text-fig. 1). Tilting the figure to the

right, a more accurate indication of the shape of the lower part of the crown is obtained. This habitus, accentuated by the long tapering arms, is apparently different from *T. stultus* and perhaps more like *T. sturtzi,* var. *spinifer* W. E. Schmidt from the Lower Devonian of Germany, (Schmidt, pl. 34, fig. 1). Again, the column in the Cornish specimen agrees so far with that of *T. stultus* in not expanding at the cup. This, an unusual feature in *Taxocrinus,* is common to both these forms; in other respects, however, the column of *T. delabolei* is different. It seems to be very regular in character throughout and certainly does not show in the proximal region the contractions, irregularity in width and specially thick nodular columnals of *T. stultus.* Nor does it show the thin columnals of that species next to the cup. The Cornish specimen therefore appears to belong to a new form which, while apparently closely allied to *T. stultus,* differs from it in having a broader habitus, probably longer and more slender arms, and a column more uniformly regular throughout.

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VII.—AREAS OF SEDIMENTATION OF LOWER CARBONIFEROUS AGE IN THE MIDLAND VALLEY OF SCOTLAND

BY

J. E. RICHEY, M.C., Sc.D.

Plate VI : Text-figures 1-3.

INTRODUCTION

THE Lower Carboniferous of Scotland is developed chiefly in the Midland Valley, which is bounded by two east-north-easterly extending lines of fracture, the Highland Boundary and the Southern Uplands Faults. It consists mainly of two great subdivisions, the Calciferous Sandstone and the Carboniferous Limestone Series. In addition, above the Carboniferous Limestone, the lower third of the Scottish Millstone Grit is included, and the top of the Lower Carboniferous is drawn at a palaeontological line which is marked by a plant and fish break. The base of the formation cannot be accurately defined, for fossil evidence is scanty and there is a lithological passage upwards from typical Upper Old Red Sandstone strata with cornstones into the Cementstone Group, the lower of two groups that constitute the Calciferous Sandstone Series. The upper or Oil-Shale Group is well developed in the area around Edinburgh and westwards to beyond Bathgate, but elsewhere it changes in facies, or is in large part absent.

Carboniferous lavas are widely distributed in the Midland Valley. Eruption took place mainly before the oil-shales were laid down, but it was renewed sporadically around Edinburgh during Oil-Shale Group times. Towards the close of this epoch it became very pronounced in the Bathgate district, where it continued throughout the greater part of the Carboniferous Limestone period. During Millstone Grit times vulcanicity recurred in Ayrshire.

In the Cementstone Group there are no well-marked horizons that can be traced over the whole area. The contemporaneous and widely distributed lavas not only interrupted sedimentation during their period of eruption but also formed land-masses against which the strata belonging to the Oil-Shale Group overlapped. Though the stratigraphy of the Calciferous Sandstone Series is well known in its broader outlines, it cannot be worked out in detail, except for the Oil-Shale Group in the Lothians. In the case of the Carboniferous Limestone Series the situation is very different. The Series is made up of a succession of rhythmic sequences, each of which, when complete, begins with a marine

bed of limestone or shale and ends with a seam of coal. The marine beds in particular are comparatively easily traced from district to district and afford numerous horizons of extreme value to the stratigrapher. The limestones are practically confined to the lower and upper parts of the Series. In the middle portion the lower beds of the rhythmic sequences are usually absent and the upper beds, including seams of coal and ironstone, are especially well developed. The Series is thus naturally divided into three groups, the Lower Limestone Group, the Limestone Coal Group and the Upper Limestone Group.

It has been known since the Geological Survey started its intensive study of the Scottish Carboniferous rocks in the year 1867 that the Carboniferous Limestone Series is prone to vary in thickness between wide limits when followed from place to place in the Midland Valley. It seems, however, that the first real clue to the reason for the variations was not obtained till 1902 when the late Professor R. W. Dron published his book on the coal-fields of Scotland.[1] In Central Ayrshire he recognized that the Limestone Coal Group abruptly changed in thickness when traced across a north-easterly extending fault (the Kerse Loch Fault, *see* Pl. VI) which traversed the beds concerned. As early as the year 1885 the late Dr. B. N. Peach in an address to the Royal Physical Society of Edinburgh gave an illuminating account of the conditions under which the Carboniferous rocks of Scotland were laid down.[2] He drew attention to the rhythmic character of the sedimentation and pointed out that the formation of each marine bed in the Carboniferous Limestone Series was ushered in by a relatively rapid downward movement of the earth's crust which was accompanied by a transgression of the sea, and that silting up followed and finally a coal seam was formed. The area in fact did not subside continuously but in a series of jerks. Peach had indeed many years previous to Dron's discovery considered that the absence of the Carboniferous Limestone Series beneath the Coal Measures of the Sanquhar Coalfield to the south-east of the Southern Uplands Fault was due to the existence of a great fault-scarp facing towards the north at the time when the Carboniferous Limestone Series was being deposited.[3] There is no doubt that we owe a great debt to Peach's inspiration in the studies that followed.

In North Ayrshire, in the years that immediately preceded the outbreak of the great war, Survey geologists, especially, I think, Mr. G. V. Wilson, realized that the north-easterly extending Dusk Water Fault coincided closely with a marked lateral variation in thickness of the Limestone Coal Group. Just after the war another fault in North Ayrshire, across which this group was

[1] Dron, R. W., 'The Coal-Fields of Scotland,' 1902, pp. 16-17.

[2] Peach, B. N., President's Address (1885), *Proc. Roy. Soc. Edinburgh*, vol. ix, 1888, pp. 17-18; *see also* a later address: 'Some Points in the Natural History of the Carboniferous Period in East Scotland,' *Proc. Roy. Soc. Edinburgh*, vol. xix, 1915, p. 237.

[3] Peach, B.N., *in* 'Explanation of Sheet 15' (*Mem. Geol. Surv.*), 1871, p. 32.

found to change abruptly in thickness, was recognized by Dr. E. M. Anderson. This, the Inchgotrick Fault, divided in two the portion of Ayrshire that lies between the Dusk Water Fault to the north and the Kerse Loch Fault (the Dron Line) to the south. Subsequent work during the survey of Central Ayrshire, especially by Messrs. V. A. Eyles and A. G. MacGregor, confirmed the reality of the Dron Line. Thus in Ayrshire it came to be known that the Carboniferous Limestone Series, and the Limestone Coal Group in particular, showed marked changes in thickness when traced from north to south across three lines of fault. The faults concerned traverse these beds, but it was evident that differential movements along the same lines had taken place during the deposition of the Carboniferous strata themselves.

While Dr. Anderson was engaged in assembling the evidence concerning the variations of the Limestone Coal Group and Upper Limestone Group across the Dusk Water and Inchgotrick Faults,[1] the writer was concerned with the correlation of the various limestones of the Lower Limestone Group and underlying Upper Calciferous Sandstone sediments (the uppermost beds of the Oil-Shale Group). This investigation led to a consideration of the variation in thickness in a north-easterly direction towards Glasgow and the Central Coalfield of the Lower Limestone Group and also of the Limestone Coal Group. It was found[2] that in the area to the north-west of the Dusk Water Fault these groups increased in thickness gradually when traced north-eastwards. Further, though the Dusk Water Fault itself came to an end near the northern limit of Ayrshire, it was realized that a continuation of this line would serve to separate areas in the Central Coalfield where marked differences in thickness occurred. The term, *Line of Variation,* was therefore applied to designate a line, whether it were coincident with an observed fault or not, across which relatively abrupt variations in thickness took place.[3] These conclusions suggested an application of the research which had yielded such interesting results to the geologists working in Ayrshire to other parts of the Midland Valley. While this task was in progress, local variations across north-easterly lines were recognized by other surveyors, by Mr. G. Ross in the Douglas Coalfield of Lanarkshire and by Mr. J. K. Allan[4] in Central Fife. Meantime also a valuable account of the stratigraphy of the Scottish Carboniferous was given by Dr. M. Macgregor,[5] which comprised a part of his address as president of the Geologi-

[1] Anderson, E. M., 'Economic Geology of the Ayrshire Coalfields, Area II' (*Mem. Geol. Surv.*), 1925, pp. 11, 12; *and in* 'The Geology of North Ayrshire' (*Mem. Geol. Surv.*), 1930, pp. 194-196.

[2] Richey, J. E., 'The Carboniferous Strata below the Top Hosie Limestone in North Ayrshire,' *Trans. Geol. Soc. Glasgow*, vol. xvii, part ii, 1925, pp. 229, 230.

[3] Richey, J. E., *in* 'The Geology of North Ayrshire' (*Mem. Geol. Surv.*), 1930, pp. 180, 181 and Fig. 16.

[4] Allan, J. K., *in* 'Economic Geology of the Fife Coalfields, Area II' (*Mem. Geol. Surv.*), 1934, p. 105.

[5] Macgregor, M., 'Scottish Carboniferous Stratigraphy: An Introduction to the Study of the Carboniferous Rocks of Scotland,' *Trans. Geol. Soc. Glasgow*, vol. xviii, part iii, 1931, pp. 442-558. Issued separately 1930.

cal Society of Glasgow. In this address and in subsequent lectures Dr. Macgregor also dealt at some length with the conditions governing the deposition of the beds, and in connexion with the Carboniferous Limestone Series he referred to the Ayrshire variations in thickness across faults and also to the variations made out by Mr. Allan around the nose of an anticline in Fife. No extensions of the Ayrshire lines of variation, however, were suggested.

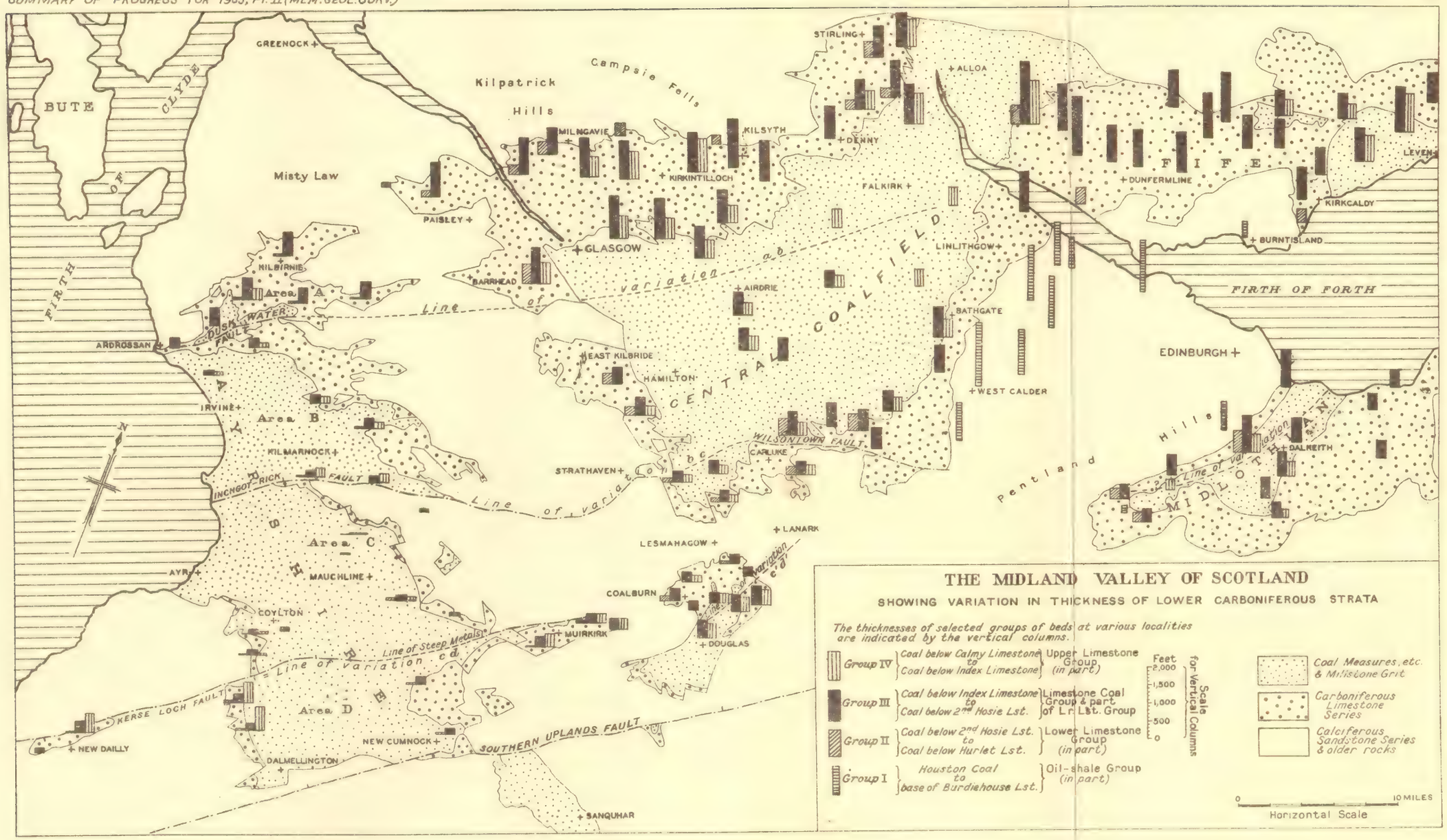
Shortly after the publication of Dr. Macgregor's work on the stratigraphy, in 1930, the writer completed his map of the Midland Valley in order to show how the three groups of the Carboniferous Limestone Series varied in thickness. This map, which is reproduced with some changes and additions as Plate VI of this paper, clearly demonstrated that all four areas of deposition already recognized in Ayrshire extended farther to the east-north-east. The corresponding lines of variation can be drawn with confidence across the western half of the Midland Valley, but only one of them locally, near Carluke, follows an exposed fault, the Wilsontown Fault. The conclusions were considered to be of importance by Dr. Macgregor, who, on account of the economic value of the Limestone Coal Group and of any evidence bearing upon its variation in thickness, undertook to verify the writer's results, in collaboration with Mr. W. Manson, and to present them in the first place to the Mining Institute of Scotland.[1]

These results may be stated here without much detailed stratigraphical argument. The thicknesses of the three groups of the Carboniferous Limestone Series are now well ascertained throughout the Midland Valley. The correlations of the various index-beds have been very carefully gone into by Scottish surveyors during the revision of the coalfields, which was begun in the year 1902 and is now practically completed.

Cycles of Sedimentation

It is well known that rhythmic sedimentation is characteristic of much of the Carboniferous system in Britain. This is especially true of Scotland, where the Carboniferous strata are very largely composed of inshore and estuarine deposits. These were laid down over a gradually sinking area, and they repeatedly raised the surface within reach of the growth of vegetation. Coal seams resting upon seat-earths (fireclays with rootlets) are thus a recurrent feature of the succession, especially of the Carboniferous Limestone Series and the Coal Measures. Here and also in other parts of the system rhythmic sequences occur. The sequences differ in their details in different parts of the system, but, as Peach so strongly advocated in regard to the Carboniferous Limestone Series, they may all be explained by supposing that subsidence of the region took place spasmodically. Shorter periods of relatively

[1] Macgregor, M. and W. Manson, 'Variations in the Thickness of the Carboniferous Limestone Series of Scotland, with Special Reference to the Limestone Coal Group,' *Trans. Instit. Mining Engineers*, vol. lxxxix, part 2, 1935, pp. 115-130.



THE MIDLAND VALLEY OF SCOTLAND

SHOWING VARIATION IN THICKNESS OF LOWER CARBONIFEROUS STRATA

The thicknesses of selected groups of beds at various localities are indicated by the vertical columns.

Group IV	Coal below Calmy Limestone to Coal below Index Limestone	Upper Limestone Group (in part)
Group III	Coal below Index Limestone to Coal below 2nd Hosie Lst.	Limestone Coal Group & part of L.r. Lst. Group
Group II	Coal below 2nd Hosie Lst. to Coal below Hurlet Lst.	Lower Limestone Group (in part)
Group I	Houston Coal to base of Burdiehouse Lst.	Oil-shale Group (in part)

Feet: 2,000 · 1,500 · 1,000 · 500 · 0 — Scale for Vertical Columns

- Coal Measures, etc. & Millstone Grit
- Carboniferous Limestone Series
- Calciferous Sandstone Series & older rocks

0 — 10 MILES
Horizontal Scale

rapid depression alternated with longer intervals of stability or of relatively slow downward movement.

We are here concerned mainly with the Carboniferous Limestone Series, and in this part of the succession the development of the rhythmic sequences is especially striking. A complete cycle of sedimentation consists of the following beds, in descending order :—

Rhythmic Cycle in the Carboniferous Limestone Series

11. Coal.
10. Fireclay with rootlets.
9. Shale.
8. Sandy shale.
7. Sandstone.
6. Sandy shale.
5. Shale, often bituminous, with :—
   b. Estuarine fish remains, and
   a. *Lingula*.
4. Calcareous shale, with :—
   b. Lamellibranchs.
   a. Brachiopods and other typical marine fossils.
3. Limestone, with marine fossils.
2. Calcareous shale, with :—
   b. Brachiopods and other typical marine fossils.
   a. Lamellibranchs.
1. Shale, often bituminous, with :—
   b. *Lingula*, and
   a. Estuarine fish remains.

The lower part of the above sequence, below the limestone, is often absent entirely, and is seldom represented by more than a few feet of sediment. In the thinness of its development and in its succession of fossils it indicates a relatively rapid downward movement of the surface over which coal had, just previously, been accumulated. The incoming of limestone marks the end of the main downward movement, and the upper part of the sequence points to the gradual silting-up of an area over which a wide expanse of sea gave place to inshore and estuarine and, finally, to terrestrial conditions.[1]

Uplift of the land-masses from which the sediments were derived and rejuvenation of the rivers must have occurred repeatedly, but within the region of sedimentation upward movements were probably infrequent. A good instance is supplied by the fact that fireclay pierced by rootlets rests upon the eroded top of the Hurlet Limestone over a large part of Ayrshire. It is also to be noted that erosion is demonstrable in some places at the base of massive sandstones.

In the upper half of the Oil-Shale Group, the variations in

[1] For recent discussions of analogous sequences in England and Wales *see* L. H. Tonks and R. C. B. Jones *in* ' The Geology of Manchester ' (*Mem. Geol. Surv.*), 1931, pp. 10-13 ; T. Robertson, ' The Geology of the South Wales Coalfield. Part V. The Country around Merthyr Tydfil ' (*Mem. Geol. Surv.*), 1932, pp. 87-89 ; *and* F. M. Trotter and S. E. Hollingworth, ' The Geology of the Brampton District ' (*Mem. Geol. Surv.*), 1932, pp. 17-19.

thickness of which are also considered in this paper, thick beds of shale alternate with sandstone. One or more seams of oil-shale are frequently intercalated with the shales. According to recent views algae contributed largely to produce this peculiar type of deposit. Beds of marl and fireclay are occasionally met with, and several marine bands also occur. Usually an oil-shale is found not far above each marine band. Rarely a coal seam occurs below. A cycle of sedimentation in the Oil-Shale Group, representing the silting-up process, would therefore appear to consist of the following beds in descending order :—

Rhythmic Cycle in the Oil-Shale Group

7. Coal.
6. Fireclay.
5. Sandstone.
3. Oil-shale. ⎫ often alternating with
4. Shale. ⎭ one another.
2. Marine band.
1. Shale.

It is exceptional to find that a complete cycle of sedimentation is represented. The majority of the rhythmic sequences consists of only a portion of the full cycle. In the Oil-Shale Group the lower and upper beds of the cycle are rarely developed. In the Lower Limestone Group the upper parts are frequently omitted owing to a renewed transgression of the sea before inshore and terrestrial conditions intervened. Thus in its upper half (the Hosie sub-group) there are in the West of Scotland four or five distinct limestones which are separated by shales (in some places accompanied by sandstone), and only one seam of fireclay, which is in some places overlain by a coal. In the Limestone Coal Group marine shales are infrequent, and only one of these horizons, the Johnstone Shell-bed, is represented by limestone locally (the Slingstane Limestone). Here the great majority of the rhythmic sequences consists of the upper part of the cycle, which usually begins with a bed of shale, often with fish remains or plants, and ends with a seam of coal. In the Upper Limestone Group, in which four or five limestones are generally developed, the most complete examples are found. The limestones are much more widely spaced than in the Lower Limestone Group, so that the upper part of the cycle is, as a rule, well represented. On the other hand the lower part, beneath the limestone, is often curtailed. In the case of the rhythmic sequence that includes the Calmy Limestone, however, the lower portion of the cycle is usually present. In the Caaf Water near Dalry in North Ayrshire, for example, lamellibranchs—a characteristic fossil is '*Edmondia*' *punctatella*—are succeeded by cephalopods and these in turn by a typical marine fauna. Curtailment of the top of the cycle is also met with. For example, coal is in some places absent beneath the second lowest limestone, the Lyoncross, and the limestone rests directly upon shales or sandstone.

Reductions are also very evident between areas where the amount of sedimentation is large and where it is small. The lateral variation in thickness of a particular group may be due to a general thinning of the rhythmic sequences and also to the absence or poor development of some of them. An extreme case may be stated. Near Gilmerton in Midlothian, where the Limestone Coal Group is well developed, as many as 30 rhythmic sequences occur in a thickness of 900 feet of sediment, the top of each marked by a seam of coal. Where the group is most reduced, near Mauchline, in Central Ayrshire, it is represented merely by some 40 feet of sandstone.

The lateral variations in the rhythmic sequences make detailed correlations difficult, except in the case of those that include marine beds. The limestones and marine shales extend in most instances in a remarkably uniform manner over the Midland Valley. By their means the broader correlations, embracing groups of strata and including many rhythmic sequences, can be made in most cases with certainty. Further, the rhythmic sequences lead us to appreciate the repeated occurrence of spasmodic downward movements which controlled the amount of sediment deposited.

Lateral Variation in Thickness of the Carboniferous Limestone Series

In a particular district, when a reduction in total thickness is met with, each part of the succession as measured between any two reliable index-beds is generally reduced in proportion. The thinning affects every part of the Series. If we look at matters in a broader way, we find that where the Limestone Coal Group is curtailed the Lower Limestone and Upper Limestone Groups are as a rule correspondingly thinner. This rule is not without its exceptions. For example, in Ayrshire, in area D (Pl. VI) the two lower groups of the Series are much thinner than in area A, but the Upper Limestone Group is much thicker. It may be added that the Upper Limestone Group contains a larger number of limestones in area D, Ayrshire, than in any other part of the Midland Valley with the exception of the related part of the Douglas Coalfield.

For our present purpose we are concerned with the variation in thickness of a whole series of rhythmic sequences as measured between two coal seams. The coals are taken to afford a datum-level which is approximately the same in every case, so that the thickness of the intervening sediments supplies a direct measurement of the amount of crustal subsidence involved at the particular locality concerned. Four levels are selected, affording three groups of strata. These correspond closely, though not exactly, to the three groups into which the Carboniferous Limestone Series is divided.

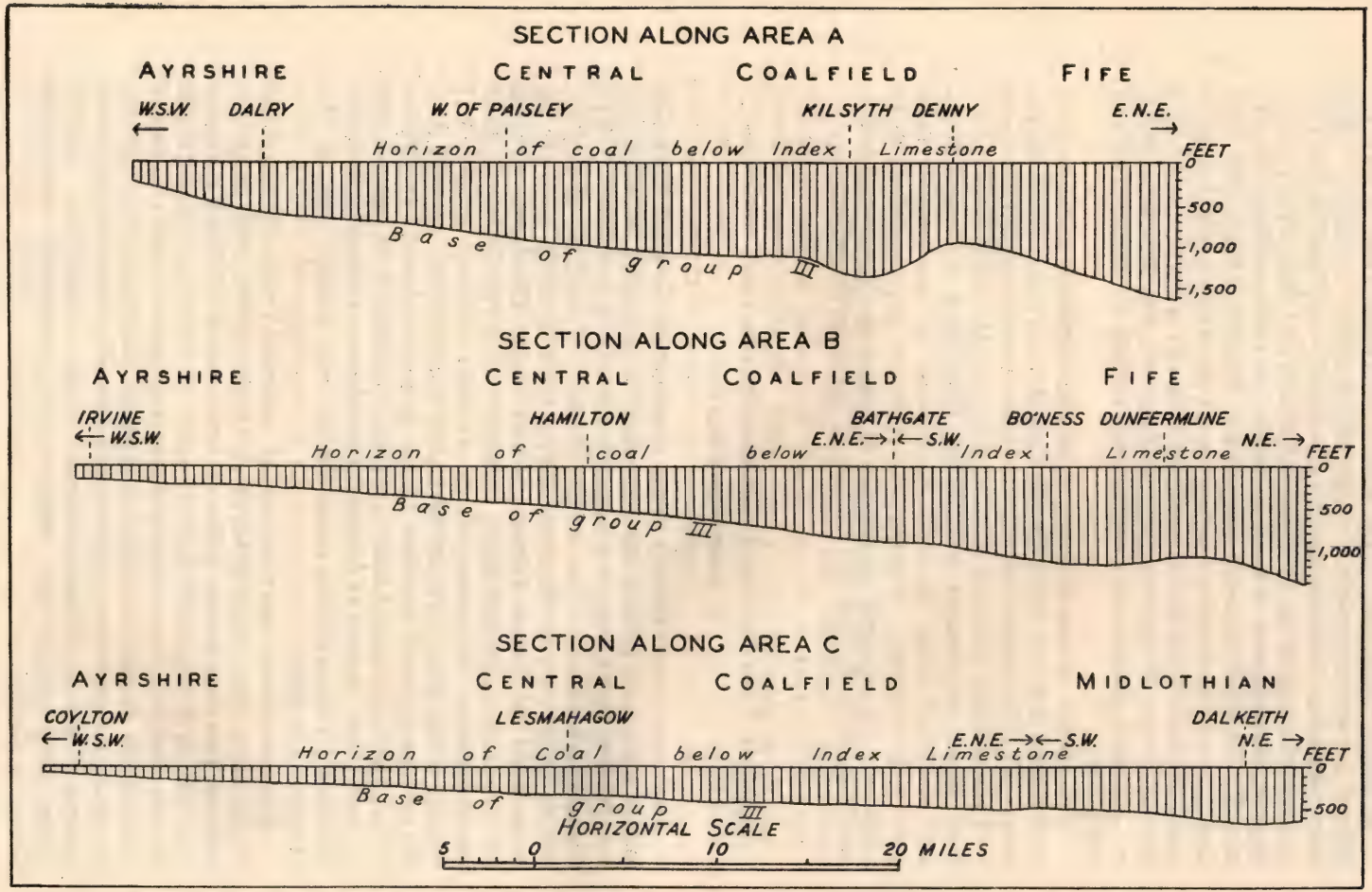


FIG. 1.—*Sections across the Midland Valley of Scotland to show gradual thickening towards the north-east of group III. (mainly Limestone Coal Group).*

The coal seams selected are as follows:—

(4) Coal beneath the Calmy Limestone [1]	Group IV = Upper Limestone Group (in large part)
(3) Coal beneath the Index Limestone	Group III = Limestone Coal Group and part of Lower Limestone Group
(2) Coal or fireclay beneath the Second Hosie Limestone	Group II = Lower Limestone Group (in large part)
(1) Coal beneath the Hurlet Limestone	

The total thicknesses of each of the three groups (II, III and IV) from well ascertained localities are plotted on Plate VI. Our information is based largely on the results of borings and partly on natural and quarry sections. In the oil-shale field of the Lothians thicknesses are also given of that part of the Oil-Shale Group which lies between the Burdiehouse Limestone and the Houston Coal (group I of Pl. VI).

The base of the vertical columns by means of which the thick-

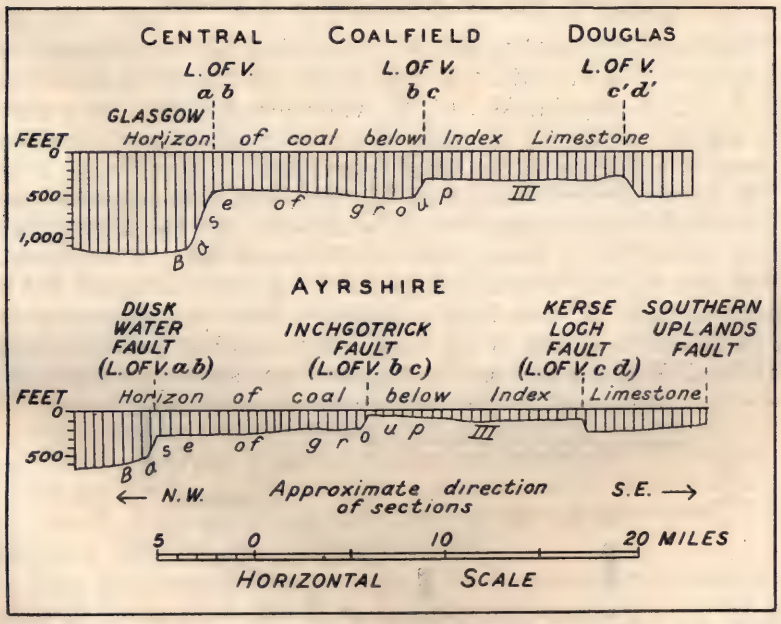


FIG. 2.—*Sections across the areas of sedimentation in the more western part of the Midland Valley of Scotland to show abrupt changes in thickness of group III. (mainly Limestone Coal Group) across the lines of variation (L. of V.).*

nesses are indicated are placed at the appropriate localities. It will be understood that the map shows only a fraction of the evidence available, and the thicknesses quoted can in general be taken as representative not only of the locality concerned but also of its immediate neighbourhood.

[1] Strata belonging to the uppermost part of the Upper Limestone Group, between the Calmy and Castlecary Limestones, are omitted from group IV because these strata are often absent or only partly represented in the Midland Valley.

It will be noted that the thicknesses of the three groups increase gradually from the west-south-west towards the east-north-east of the Midland Valley (*see* Fig. 1). Also it will be seen that from north-north-west to south-south-east abrupt changes in thickness occur (*see* Fig. 2) and that for this reason east-north-easterly extending lines can be drawn across at any rate the western part of the Midland Valley to separate the country into strips, or areas of sedimentation. Thus each of these areas is marked by an increase in thickness of the groups from west-south-west to east-north-east, and by a contrast in thickness as compared with adjoining portions of other areas.

We will now proceed to analyse the evidence as far as necessary. Plate VI presents the evidence in a concise form. It gives an abstract of the facts. With it in front of the reader little need be said.

(a) THE AREAS OF SEDIMENTATION IN AYRSHIRE

The results already achieved in this area are well known. As indicated in the Introduction (pp. 94-5), the late Professor Dron, Dr. E. M. Anderson, Mr. G. V. Wilson and others have shown that abrupt variations in thickness take place across three lines of fault which traverse the beds concerned.

A north-western area (A of Pl. VI) is in part separated from an area (B) immediately to the south-east by the Dusk Water Fault, which has a downthrow to the north-west. Over area A the strata of group III as defined above (p. 101) are much thicker than over area B, that is, the area of thicker sedimentation lies on the downthrow side of the fault. A few points are to be noted. The Dusk Water Fault and its branches are shown on Fig. 3. It

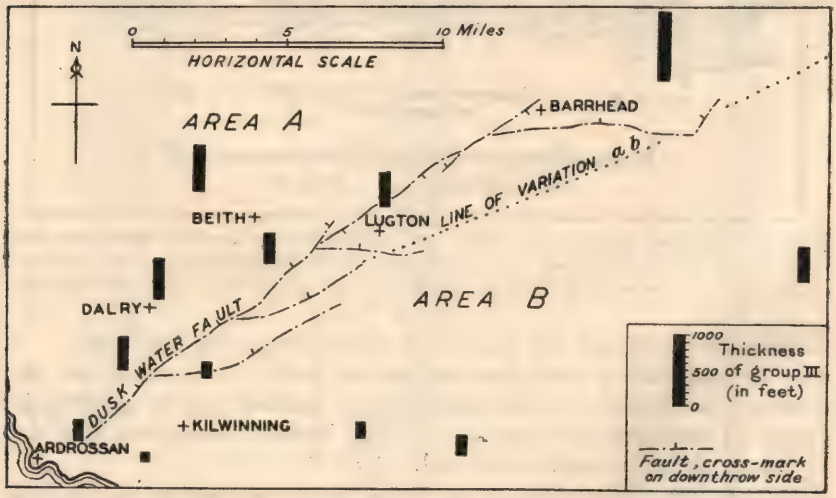


FIG. 3.—*Sketch Map to show variations in thickness of group III (mainly Limestone Coal Group) across the line of the Dusk Water Fault and its vicinity.*

will be seen that the most direct branch ends to the north-east between Beith and Lugton. In this direction its line is continued by a fault with downthrow in the opposite direction. Evidence regarding the development of group III in this district is fragmentary. It is impossible to know which of the various branches of the Dusk Water Fault was functioning during the period of sedimentation. The continuation of the Dusk Water line of variation as shown on Fig. 3 has, however, the merit of agreeing with the requirements of the evidence bearing on the mutual boundary of areas A and B in the Central Coalfield (*see* Pl. VI).

Another point to note in connexion with group III is that in area A sedimentation becomes less in the vicinity of the fault, as for example, to the south of Beith. There is, however, a gradual increase in thickness over the area towards the north-east.

Our information concerning group IV is less impressive, but it tells the same tale. Over area A the group is much thicker than over area B. But in the case of group II and of the limestone-bearing strata at the top of the underlying Calciferous Sandstone Series matters are different. Their thickness does not change immediately on either side of the Dusk Water Fault. These sediments attain their maximum development along a line which appears to cross obliquely the Dusk Water Fault. The line marks the centre of a gulf which was bounded to the north-west and south-east by land. The land was composed mainly of Calciferous Sandstone volcanic rocks. Its existence is proved by the fact that when traced towards the north-west and south-east the beds laid down along the centre of the gulf overlap one another and so come to rest on the volcanic rocks. It is concluded that movement along the fault-line did not occur to any appreciable extent until after group II was laid down. But a point of similarity to the variations of the later deposits is that group II and the underlying Upper Calciferous Sandstone sediments increase gradually in thickness in a north-easterly direction along the centre of the gulf, and that this increase is maintained in the adjoining parts of the Central Coalfield.[1]

Area B is separated from area C by the east-north-easterly extending Inchgotrick Fault, as Dr. Anderson showed. Over area C sedimentation was much less than over area B, and this is reflected in the fact that the throw of the fault is towards area B. It is of interest to note that slipping of sediments of group III, which were deposited on the upthrow side of the fault within area C, appears to have taken place at Inchgotrick during the period of sedimentation.[2]

The Inchgotrick Fault is concluded to have been moving at an early date in Lower Carboniferous times. The Calciferous Sand-

[1] *See* J. E. Richey, 'The Carboniferous Strata below the Top Hosie Limestone in North Ayrshire,' *Trans. Geol. Soc. Glasgow*, vol. xvii., part ii, 1925, pp. 229-230.

[2] Bailey, E. B., *in* 'The Geology of North Ayrshire' (*Mem. Geol. Surv.*), 1930, pp. 195-196.

stone lavas, upon which the Upper Calciferous Sandstone and later sediments rest unconformably, are at least 500 feet thick just north of the fault and are practically absent to the south.[1] This suggests that the lavas ended to the south against a fault-scarp facing north, which they barely overtopped.

It should be mentioned that there is some difficulty in correlating the limestones of group IV in areas B and C with the type area (A). It is certain, however, that a southward reduction in the development of the group takes place both at the Dusk Water and Inchgotrick Faults.

Areas C and D are separated by the Kerse Loch Fault, the line of which is continued to the east-north-east in a 'Line of Steep Metals,' which affects the Coal Measures. Here, as already stated, the late Professor Dron recognized that the Limestone Coal Group showed a marked increase in thickness on the south-eastern, downthrow, side of the fault (area D) as compared with the attenuated development characteristic of the north-western side (area C). His observations have been much extended recently by Survey officers who have clearly demonstrated the reality of the Dron line near Rankinston, 7 miles south-east of the town of Ayr.[2] Several bores show that all three groups of the Carboniferous Limestone Series and also the Millstone Grit are much thinner to the north-west of the fault at this point than to the south-east. The more scattered evidence elsewhere over areas C and D amply substantiates the conclusion that the fault was moving during Carboniferous Limestone and also Millstone Grit times.

Area C is of the nature of a horst, in that it is bounded by downthrow faults. There is, however, no evidence to show that the reduction in the amount of sediment deposited over the area is due to uplift having taken place, such as Mr. T. Eastwood has found at Crosbie in Cumberland.[3] It is believed that subsidence of the entire region marked practically the whole of the Carboniferous Limestone period in Ayrshire, but that in area C downward movements took place to a less extent than in the areas to the north and south. Indeed, a large part of area C must have been a mere shoal with a practically stationary floor during much of the period.

Area D is naturally bounded to the south-east by the Southern Uplands Fault, on the upthrow side of which, in the western part of the Sanquhar Coalfield, the Carboniferous Limestone Series is absent. It is represented at the eastern end of the Sanquhar district but is transgressed westwards by the Upper Carboniferous. The latter is seen in many sections to rest directly upon pre-Carboniferous (Ordovician) strata. In only one exposure towards the west are Lower Carboniferous beds known to occur. They perhaps

[1] Richey, J. E., *op. cit.*, pp. 205-206.

[2] Eyles, V. A., and A. G. MacGregor *in* 'Economic Geology of the Ayrshire Coalfields, Area IV' (*Mem. Geol. Surv.*), 1932, pp. 9-12.

[3] Eastwood, T., 'The Geology of the Maryport District' (*Mem. Geol. Surv.*), 1930, p. 98 and Fig. 17.

belong to the lower third of the Scottish Millstone Grit, and are overlain unconformably by Upper Carboniferous strata.[1] Near the fault, therefore, the Lower Carboniferous may never have been laid down at all. The entire absence of the Calciferous Sandstone Series and of the underlying Old Red Sandstone on the upthrow side of the fault is also very significant. As Peach suggested, movement along the fault would appear to have taken place during Lower Carboniferous times. Near New Cumnock, however, just west of the Sanquhar basin, Lower Carboniferous sediments have been mapped across the line of the fault, as though at this point the movements along the fracture were in part earlier than and in part contemporaneous with the deposition of the beds concerned.[2]

(b) CONTINUATIONS OF THE AYRSHIRE AREAS OF SEDIMENTATION IN THE CENTRAL PART OF THE MIDLAND VALLEY

In the Central Coalfield marked variations in thickness of the Carboniferous Limestone Series are found to take place, but they could hardly have been understood by themselves. In only one district, near Carluke, are they located with reference to an exposed fault. Ayrshire provides the key to the problem.

Area A.—The Series outcrops along the northern side of the Central Coalfield and for the most part increases gradually in thickness when it is traced from the country west of Paisley east-north-eastwards across the Clyde towards Kirkintilloch and Kilsyth. North of the Clyde, on the northern outskirts of Glasgow and south-west of Milngavie, a local decrease in group III is found. At Kilsyth a greater increase than usual is encountered, and is succeeded farther to the north-east, at Denny, by a local curtailment (*see* Fig. 2). With these exceptions the increase proceeds uniformly into Western Fife, where groups III and IV attain their maximum thickness in Scotland.

Area B.—The area of Carboniferous Limestone exposed at the surface on the north-west side of the Central Coalfield is succeeded to the south-east by a wide tract of Millstone Grit and Coal Measures. These rocks have been pierced at a number of places by deep borings, which have been driven down through the Carboniferous Limestone Series far enough to ascertain the condition of its coals. In every case the Series has been found to be much thinner than along the northern crop. Where its strata again come to the surface on the south-western side of the Central Coalfield, between East Kilbride and Strathaven, a similar decrease is apparent.

It will be seen by referring to Plate VI that a continuation of the Dusk Water line of variation (ab) to the east-north-east serves to separate areas in the Central Coalfield which correspond to areas A and B of Ayrshire. North of the Forth, in Fife, varia-

[1] Simpson, J. B., *in* 'The Geology of the Sanquhar Coalfield' (*Mem. Geol. Surv.*), 1936 pp. 21, 22; *see also* Fig. 2, p. 5.

[2] *See* Six-inch Geological Map of Scotland, Ayrshire, Sheet 42 S.W., 1931.

tions in thickness have also been recognized. This district is not dealt with to any extent in the present paper; but it may be stated on the authority of Messrs. Haldane, Allan and Knox that the variations are less abrupt than in Ayrshire and are related to contemporaneous folding and not, so far as is known, to faulting. The folding took place along north-east axes, and some relationship between the folds and the lines of variation recognized farther west may perhaps emerge.

In the Central Coalfield, area B extends south-eastwards for many miles and underlies a large part of the great central basin of Coal Measures which has been the scene of so much mining activity. To the north-east of this basin the Carboniferous Limestone Series again outcrops, but here, around Bathgate, its usefulness from the mining point of view is curtailed owing to the occurrence of contemporaneous igneous rocks. Thicknesses quoted from this district for groups III and IV on Plate VI include lavas and ashes. The volcanic rocks, however, are interbedded with normal sediments, and these indicate clearly the positions of the beds that are chosen as the limits for groups III and IV (*see* p. 101). It is therefore correct to group the volcanic rocks with the sediments in arriving at the thicknesses of groups III and IV in this district.

As Macgregor and Manson have shown, the volcanic group appears to come to an end to the north-west, close to the line of variation (ab). The authors concerned have stated that this is a suggestive fact.[1] There cannot, however, be any reason to suppose that the lavas terminated against a fault-scarp coincident with the line (ab). If a fault-scarp was developed here, it would have faced towards the north-west and therefore could not have acted as a barrier to lavas flowing from the south-east.

The area of reduced sedimentation (B) continues southwards as far as the Wilsontown Fault, beyond which, on the upthrow side of the fault, an abrupt further decrease is found. The fault is approximately in line with a continuation of the Inchgotrick Fault of Ayrshire (line of variation bc), on the northern side of which, near Strathaven, Calciferous Sandstone lavas are brought down against Lower Old Red Sandstone and Downtonian strata. East-north-eastwards of Strathaven the continuation of the Inchgotrick Fault fails to cross a narrow syncline of Upper Carboniferous strata which occupy the valley of the Clyde. On the farther side of the syncline the Wilsontown Fault begins. It is probable that the Wilsontown Fault was actually continuous with the Inchgotrick Fault during Lower Carboniferous times. At any rate an extension across the valley of the Clyde during the deposition of the Oil-Shale Group serves to explain a difficulty which has long been realised.

When the part of the Oil Shale Group, which we here term group I in Plate VI, is followed southwards from West Calder where it attains its maximum development towards the Wilson-

[1] Macgregor, M., and W. Manson, *op. cit.*, p. 122.

town Fault, it decreases in thickness; at the same time oil-shales become thinner and sandstone increases at the expense of shales. South of the fault oil-shales disappear and the sequence consists largely of sandstone and marl. As Mr. R. G. Carruthers concluded,[1] the deterioration of the group points to the existence of a shore-line to the south. The sandy and marly development continues, on the southern side of the fault, south-westwards to Carluke. Farther west, however, to the north-east of Strathaven, group I reverts to its West Calder facies, except that only the upper third of the group is represented. The beds rest unconformably upon the Calciferous Sandstone lavas, and it is evident that along this widespread plane of unconformity the lower part of the Oil-Shale Group has been cut out by overlap. It is noteworthy that the Strathaven succession has been correlated bed by bed with the corresponding part of the West Calder sequence.

The apparent isolation of the Strathaven oil-shale development from the main shale-field has been explained in the past by invoking the presence of a connecting strait.[2] It may now be suggested further that differential movements along the line of the Wilsontown Fault during the Oil-Shale period would best account for the contrast between the sedimentation in the areas on either side of the fault. This explanation seems all the more likely when we recall that the correlated Inchgotrick Fault is considered to have been in existence in Ayrshire at an earlier date than even the Oil-Shale Group, in fact, during the eruption of the Calciferous Sandstone lavas (pp. 103-4). Further, at Strathaven, the contrast in the development of the Calciferous Sandstone Series on either side of the line (bc) is remarkably striking. To the north the Calciferous Sandstone lavas that are overlain unconformably by the upper part of the Oil-Shale Group belong to the uppermost portion of the great volcanic group of the Clyde Plateau.[3] The volcanic group at Strathaven may well reach a thickness of a thousand feet or more. To this are to be added about 400 feet belonging to the upper portion of the Oil-Shale Group. South of the fault, on the other hand, only a meagre thickness of Calciferous Sandstone lavas and sediments intervenes between the Lower Old Red Sandstone and the base of the Carboniferous Limestone Series. The Upper Old Red Sandstone, the sediments of the Cementstone Group, and almost all of the Calciferous Sandstone volcanic group and Upper Calciferous Sandstone sediments (the uppermost beds of the Oil-Shale Group) are absent. Such a difference in development is explained if we suppose that at this point along the line of the Inchgotrick and Wilsontown Faults a fault-scarp facing north was constantly renewed by movement during the Calciferous Sandstone period.

[1] Carruthers, R. G., *in* 'The Oil-Shales of the Lothians,' 3rd edit. (*Mem. Geol. Surv.*), 1927, p. 19.

[2] Dinham, C. H., *in* 'Economic Geology of the Central Coalfield, Area IX' (*Mem. Geol. Surv.*), 1921, p. 9.

[3] Richey, J. E., 'The North Ayrshire Sequence of Calciferous Sandstone Volcanic Rocks,' *Trans. Geol. Soc. Glasgow*, vol. xviii, part ii, 1928, p. 248.

Area C.—The Carboniferous Limestone Series suffers a reduction in thickness as the Wilsontown Fault is crossed in a southerly direction, and there can be no doubt that the area to the south corresponds with area C of Ayrshire when we take into account the gradual increase in thickness of the Series as it is traced from west to east.

In Ayrshire the southern limit of area C is the Kerse Loch Fault or Dron Line (cd). This line extends east-north-eastwards in the 'Line of Steep Metals' to connect with a fault that bounds the northern side of the Muirkirk Coalfield. This isolated area of Carboniferous Limestone strata belongs in part at least to area D of Ayrshire, but its sequence is also closely comparable with that found to the north-east in the southern part of area C. Here, in the Douglas Coalfield, there is a marked contrast in the thickness of groups III and IV on either side of a north-easterly line that extends along the centre of this isolated basin of Coal Measures. No differential movements of Lower Carboniferous date are apparent between the district north-west of the Douglas Coalfield line (c^1d^1) and the adjacent part of the Muirkirk district. The line cd might be considered to come to an end north-east of Muirkirk and the line c^1d^1 be regarded as a separate line of variation, though it certainly forms the southern boundary of area C of the Central and Douglas Coalfields. This question is discussed further below.

Area D.—As mentioned above, area D of Ayrshire includes much at least of the Muirkirk Coalfield. Farther to the east-north-east the development on the south-east side of the Douglas Coalfield line (c^1d^1) is much greater than that at Muirkirk. But it is comparable in the number of limestones which are found in the Upper Limestone Group with the sequence met with many miles away in area D of Ayrshire to the north of Dalmellington and elsewhere (p. 99). Also, a high proportion of coal relatively to other strata in group III is characteristic of the areas (D and D^1) to the south-east of the lines cd and c^1d^1. A connexion between the lines cd and c^1d^1 is not altogether ruled out. Possibly the line cd departs from the northern boundary fault of the Muirkirk Coalfield to cross this field at its north-eastern end and so connect on to the Douglas Coalfield line. The fact that groups III and IV are somewhat less thick at the north-eastern end of the Muirkirk basin than at the south-western end suggests such a course. If the basin were supposed to lie wholly within the same area of sedimentation, an *increase* towards the north-east might be expected to take place.

Let us now journey eastwards from Carluke over extensive outcrops of rocks earlier than the Carboniferous Limestone Series to the southern end of the Midlothian Coalfield. Here the Series is only slightly thicker than in area C near Carluke, but along the north-western side of the Midlothian basin an abrupt increase takes place. A north-easterly extending line drawn along the centre of the Midlothian Coalfield would serve to separate different develop-

ments of the Carboniferous Limestone Series and also of the Oil-Shale Group (group I). At the southern end of the coalfield, near Carlops, the beds between the limits selected for group I are only about 200 feet in thickness. Along the western side of the coalfield, at Straiton, these beds are 690 feet thick.

The Midlothian Coalfield awaits a second revision, and it would be premature to express any definite opinion from the evidence at present available. It may, however, be pointed out that the supposed Midlothian line runs in a north-easterly direction, parallel to the axes of the contemporaneous folds in Fife.

The development of group I at Straiton is in its turn much less than that found in the main oil-shale field around West Calder, 15 miles to the west. Older strata occupy the intervening ground, and it is impossible to offer a definite explanation of the contrast. Another marked decrease in group I occurs at Burntisland in Fife, but neither in this case can its exact significance be assessed at the present time.

In Fife, as already stated, the geologists concerned think that local folding took place along north-east or north-north-east axes during the deposition of the Carboniferous Limestone Series. A different problem is presented here from that in Ayrshire. Variations in thickness are related to existing folds and not, as far as is known, to faults. The connexion, if any, between the tectonic disturbances governing sedimentation in the West and the East of Scotland is a question that remains for future workers to decide.

Conclusion

In Ayrshire, and in the Central Coalfield in the case of the Wilsontown Fault, the lines of variation correspond to faults that were moving during the deposition of the Carboniferous Limestone Series. It may be surmised that the faults represent renewed movement along Caledonian lines in the Midland Valley area. It is known that the fractures which bound this region, the Highland Boundary and Southern Uplands Faults, have a long history behind them, and that they were moving prior to, as well as subsequently to, the deposition of the Upper Old Red Sandstone. It is possible that Caledonian fractures affected the older (pre-Upper Old Red Sandstone) rocks within the Midland Valley itself and that renewed movements along some of them took place during the period when the Lower Carboniferous strata were being laid down. Such movements may have been reflected in many places in the sediments themselves in monoclinal folding and not in actual faulting.

On the other hand the area was certainly under regional tensional stress that produced east-north-easterly fractures during Lower Carboniferous times. There is evidence of this in the Lower Carboniferous dykes with their dominant east-north-easterly

trend around the Misty Law vent south of the Clyde estuary and the Meikle Bin vent in the Campsie Fells north of Glasgow. The area was without doubt part of a region of stretching and subsidence and of pronounced volcanic activity during the Lower Carboniferous period. Furthermore, the contemporaneous fault-movements of the West of Scotland would appear to be replaced by folding towards the east, especially in the case of Fife. The situation is thus complicated. Its further elucidation must await the considered opinion of the geologists at present engaged in Fife and Midlothian.

At the close of the Lower Carboniferous period uplift is proved to have occurred in various places where the Upper Carboniferous rests unconformably upon earlier strata. This uplift, however, may be correlated with a much more widespread crustal movement than the local differential movements we are dealing with. It preceded a period of sedimentation and regional subsidence during the Coal Measures, when differential movements seem to have been of less account than in Lower Carboniferous times, or at any rate appear to have followed mainly new lines in the Midland Valley of Scotland.

Acknowledgments

In the text sufficient acknowledgments have, I hope, been made to those who originated the research in Ayrshire of which this paper is an extension. To colleagues on the Scottish Survey, past and present, who have laboriously worked out the details of Lower Carboniferous stratigraphy in the Central and Douglas Coalfields it is difficult to pay adequate tribute. For information concerning the problems presented by the East of Scotland I am indebted to Mr. Allan, Mr. Haldane and Mr. Knox. For his encouragement of my earlier efforts while I was a member of his unit on the Scottish Survey, and for advising their extension, I wish to record my thanks to Prof. E. B. Bailey. I am grateful also to Mr. T. Eastwood for reading my manuscript and for making many useful suggestions.

VIII.—WASHOUTS IN THE HAIGH MOOR COAL OF WEST YORKSHIRE

BY

WILFRID EDWARDS, M.A.

Text-figures 1 and 2.

INTRODUCTION

THE occurrence of washouts or rock-faults is a conspicuous feature of the Haigh Moor Coal, the area affected amounting in the aggregate to over three square miles in a worked field of about 80 square miles. The quality of the coal is such that extraction in troubled ground is abandoned with the greatest reluctance, and thus conditions for the investigation of the washout phenomena are unusually favourable.

When the coalfield was first surveyed colliery development had not revealed the extent of the washout areas shown in Fig. 1, and only brief accounts were given in Green's memoir.[1] Later, Kendall referred to newer sections in the Whitwood district.[2] Both these observers subscribed to the generally accepted contemporaneous stream-erosion theory of Buddle,[3] though Kendall recognized the existence of features which were not explicable by such a theory alone, and in 1911 suggested a tectonic origin.[4]

In 1916 Fearnsides[5] gave a full description of the " rock-faults " in the Haigh Moor seam which were then being exposed. The characteristic features of the disturbed areas were illustrated as ' rock-jumbles ' composed of angular and slickensided fragments of sandstone, mudstone and coal, with irregular interleavings of the same materials and with lateral displacement and duplication of the seam. It was shown that the movement took place before the imposition of cleat, and it was maintained that the whole disturbance was a result of strain due to lateral stress, and that the irregular yielding arose from unequal loss of volume when water was expressed from sand and mud (*op. cit.*, p. 580).

During the resurvey of West Yorkshire the washouts have been charted over a large part of the worked area and several temporary exposures have been examined. The inference is made that con-

[1] Green, A. H., and others, 'The Geology of the Yorkshire Coalfield', (*Mem. Geol. Surv.*) 1878, pp. 334, 343-345.
[2] Kendall, P. F., and H. E. Wroot, 'The Geology of Yorkshire,' 1924, pp. 142-146.
[3] Buddle, J., ' On the Great Fault called the Horse in the Forest of Dean Coalfield,' *Trans. Geol. Soc.*, series 2, vol. vi, 1842, pp. 215-220.
[4] ' The Geology of the Districts around Settle and Harrogate,' *Proc. Geol. Assoc.*, vol. xxii, 1911, p. 43.
[5] ' Some Effects of Earth-movement on the Coal Measures of the Sheffield District (South Yorkshire and the neighbouring parts of West Yorkshire, Derbyshire, and Nottinghamshire). —Part I,' *Trans. Inst. Min. Eng.*, vol. l, 1915-16, pp. 583-608.

temporary channelling is the *primary* cause of the washouts, and that its effect is everywhere modified by distortion and shearing due to the onset and continuous application of loading-stress.

Description of the Washouts

The Haigh Moor Coal, 3½ to 4 ft. thick, is normally overlain by several feet of weak, laminated bind (mudstone) which is itself succeeded abruptly by the Haigh Moor Rock. The latter is a typical Coal Measures sandstone, fine-grained, false-bedded in the lower part, and with interbedded layers of sandy shale and bind. The roof-bind is very irregular in thickness owing to downward transgressions of the base of the overlying sandstone, and where these occur patches of sandstone are often seen to have a basal layer of rolled ironstone nodules. Thus it appears that the roof-bind is extensively channelled by washouts, the lower part of the Haigh Moor Rock being the infilling of the stream courses. Over wide belts flanking the coal-washouts, the bind is missing or occurs as thin lenses, and here under the " rock-roof " the seam displays irregularity in thickness. The zones considered to be " rock-faults " or " washouts " are those in which transgression has gone

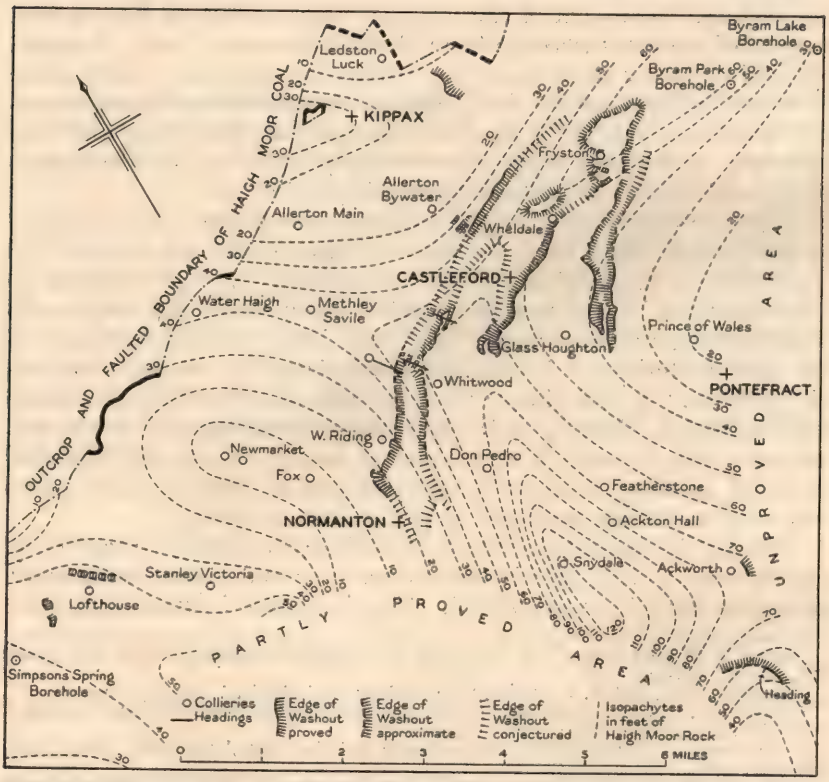


Fig. 1.—*Washouts in the Haigh Moor Coal. Isopachytes of the Haigh Moor Rock.*

farther and has either completely removed the seam or has so reduced its bulk that large areas are unworkable.

It needs emphasis that the above is in most cases only the reputed condition of the washouts. The boundaries shown in Fig. 1 are drawn where coal working has been abandoned because of these conditions; the areas enclosed by them, except for a few headings, are unexplored. They may contain no coal, but more probably they include coal in isolated patches, like those near Fryston Collieries, and in narrow strips more or less parallel to the boundaries, as in the Whitwood headings.

The distribution and thickness of the Haigh Moor Rock are shown in Fig. 1. The relation between thickness variations of the rock and position of the major washout areas is peculiar, and will be referred to again.

Details of the washout phenomena in pit workings.—The average washout channel is essentially a downward transgression of sandstone across roof-bind and coal, with a cross-section like that of a boat-bottom, but with irregular variation in the angles made by the sides. Actually, although something of the sort may often be inferred, the simple transgression is usually masked by after-effects which have modified the strata at and near the plane of erosion. These effects are (a) Distortion and creasing, (b) Interleaving of sandstone and coal, (c) Duplication of seam,[1] (d) Brecciation and lateral displacement (' Rock Jumbles ').

The first of these effects is important, for it affords evidence of yield under stress while the sediments were still plastic. Its commonest manifestation is that of ' Rock Rolls.' These are most in evidence where the coal is worked under a rock-roof. Here the nether surface of the sandstone is rucked into smooth folds, usually a few but occasionally tens of feet across, which belly down into the seam; beneath them the coal is thinner, while between them it is thicker than usual. Where the coal is thicker, bind, showing little or no trace of original bedding, is not uncommon in the arch of the fold.

There are also smaller rolls, with definite orientation, that cross the working places like great creases, and maintain a rough parallelism with the elongation of the washout area. In cross-section they resemble text-book drawings of asymmetric or recumbent folds, and only in their incipient stages has any symmetry been preserved. The bounding surfaces of the rolls are smooth, often highly slickensided, and, except where they pass into zones of ' rock-jumbling,' are characterized by flowing curves.

Similar rolls have been observed at the junction of sandstone and bind, where they occasionally form prominent rounded projections.

Distortion is not confined to the bounding surface between

[1] This has usually been considered a contemporaneous effect. *See* T. Eastwood, ' ' Nips ' and ' Rock-Riders ' in the West Cumberland Coalfield,' Summary of Progress for 1928, Part II (*Mem. Geol. Surv.*), 1929, p. 115.

sandstone and underlying beds. Occasional sections show up to 10 ft. of roof measures in which the bind between sandstone and coal, and also the lowest beds of the sandstone, exhibit broad and irregular folding of considerable complexity which may develop into slides. Distortion of bedding is also manifest in some of the large masses of sandstone which go to form the rock-jumbles described below.

Interleaving of sandstone and coal.—The phenomenon is common but is best preserved in areas where ' rock-jumbling ' has not intervened. While the examples in Fig. 2 are typical, less regular forms occur as shown by Prof. Fearnsides (*op. cit.*, pp. 15-17). The sandstone ' stringers ' are in most, possibly in all cases, in substantial continuity with the roof, towards which they tend to thicken, and they consist of compact rock identical with that forming the roof. Commonly thin layers of coal passing into hair-like ramifications, appear to have penetrated the sandstone from without.

Duplication of Seam.—While no characteristic example is at present accessible in Yorkshire, a case was demonstrated in a heading at West Riding Collieries (*see* Fig. 1), and a true-scale drawing of it is reproduced by Prof. Fearnsides (*op. cit.*, pp. 13, 14). Double seam sections are common features of washout margins, and probably no one of the explanations offered can suffice for all cases (*see* Eastwood, *op. cit.*).

Brecciation and lateral displacement.—These features have been fully discussed by Prof. Fearnsides, who shows the ' filling ' of the rock-faults he described as ungraded ' rock-jumbles ' consisting of masses of sandstone, mudstone, coal and any other rock that has been present in the disturbed zone. The sandstone occurs in large angular masses; the mudstones and stone binds (sandy shales) are more commonly lens-shaped fragments which have yielded to pressure by bending; coal forms irregular shreds and cakes, or intrudes as minor dykes and sills in cracks in and between the sandstone masses.

Slickensides polish the bounding surfaces of diverse fragments in the rock-jumbles, and are common at the junction of any two different kinds of rock throughout the washout areas.

The Causes of the Washouts

The localization of disturbance to the roof of the Haigh Moor Coal, the transgressive character of the nether surface of the sandstone rock, the presence of conglomerates, and the general plan of the washout areas shown in Fig. 1 admit of no explanation but that of contemporaneous erosion. All the evidence points to this erosion having accompanied a sudden change of sedimentation from mud to sand after a few feet of roof-bind had been deposited. It is probable that channelling of the mud surface was commoner than can be demonstrated, and that the washouts affect-

ing the coal, or those occasionally seen in the roof-bind, provide only partial evidence of the whole of the erosion phenomena.

There is not enough evidence to reconstruct the contemporary geography. The superficial likeness of the channels at Castleford to a system of delta distributaries may well be illusory, and it cannot be claimed that the washouts figured are members of a single system of interconnected streams. The balance of evidence points to excavation of the greater channels by water flowing towards the south-west, for all the strata-groups of the local measures show a tendency to thicken in that direction, *i.e.*, towards South-east Lancashire, the centre of the Carboniferous geosyncline of the

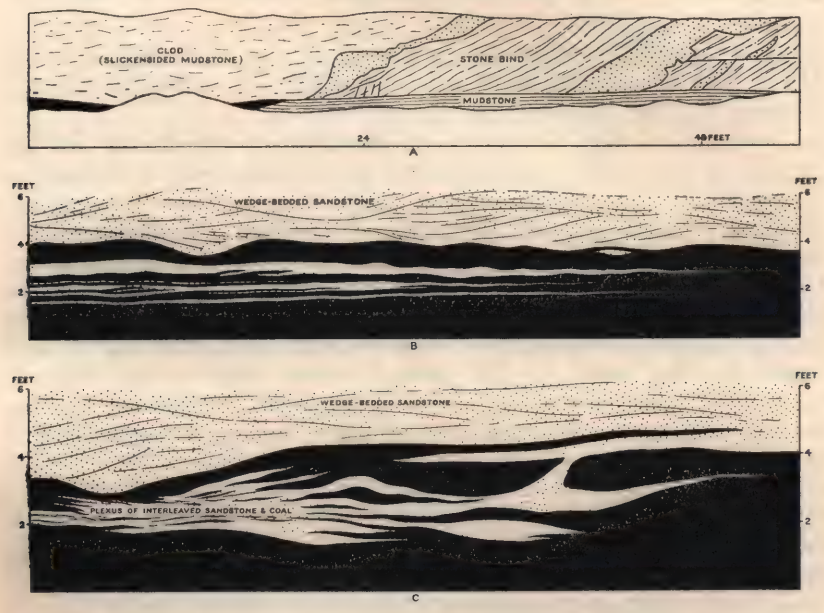


FIG. 2.—*Measured sections of washout phenomena in the Haigh Moor Seam.* A. Heading at Hemsworth Collieries, at point of disappearance of seam. B and C. Interleaved sandstone and coal, near Normanton.

Midlands.[1] A westerly flow is indicated by the false-bedding in the Hemsworth heading (Fig. 2).

The nature of the Haigh Moor Rock warrants the inference that its deposition commenced under conditions of strong current associated with bottom scour. The top of the rock is usually overlain by a thin coal and shows evidence of shoaling up to approximate water-level. Though the presence of some interbedded mud, with its greater compression-ratio (*see* p. 117) does to a minor extent vitiate this conclusion, yet it would appear that the irregularities in thickness of the rock (*see* Fig. 1) are due primarily to irregular subsidence during sedimentation, *i.e.* where the rock is

[1] Fearnsides, W. G., 'A Correlation of Structures in the Coalfields of the Midland Province,' *Rep. Brit. Assoc.* for 1933 (1934), pp. 61, 62.

thickest the bottom was subsiding most rapidly. Such irregular bottom movements were general throughout sedimentation of the productive Coal Measures of the district, but to make a quantitative assessment of the causes of the effect is not possible. One cause was undoubtedly the contraction under loading of the lenticular Coal Measures already deposited, for, as shown by Hedberg, the compaction of mudstones continues at a diminishing rate throughout a pressure-range representing loading with at least 8,000 feet of overburden.[1] Tectonic warping is suggested by the fact that all the sheets of sediment between the major coals of the district show thickness variations which tend to lie along N.W.-S.E. and N.E.-S.W. belts; these are the dominant directions of the later Permo-Carboniferous faulting. These variations reveal no local lines of persistent weakness or strength, and it is impossible to show that the stream-flow was controlled by contemporaneous folding as, for instance, in Flintshire.[2]

Scrutiny of Fig. 1 reveals an absence of washouts in the region of maximum rock-thickness at Snydale, and a disposition of the major channels in an area intervening between two regions of thick rock at Syndale and east of Fryston. A rock-roll belt south of Normanton shows a similar relation to rock-thickness. Generalization from this particular case may prove unreliable, but the tentative suggestion is made that bottom movements during sedimentation, however they were caused, controlled the courses taken by the water in its passage from land to sea, allowed maximum accumulation in areas of greatest subsidence, and by leaving barriers to the free flow of water induced channelling at such points as Castleford.

Deformation of Rocks in the Washouts

The distortion and creasing are comparable with certain types of deformation of plastic sediments by movements set up soon after their deposition under the single or combined influence of gravity and loading. The processes, usually known as *subaqueous gliding*, have been described by Bernard Smith,[3] A. W. Grabau,[4] A. Hadding,[5] and others. Hadding, in a review of the subject, lays emphasis on the loading of sediments deposited on a sloping bottom as the cause of sliding, and shows that a growing delta can press aside a plastic substratum, and that horizontal strata can slide if exposed to differential weight or to tangential pressure.

Earthquake-lurching has been postulated by Kendall as the cause of the rock-rolls and other deformations,[6] and may be

[1] Hedberg, H. D., 'Gravitational Compaction of Clays and Shales,' *Amer. Journ. Sci.*, vol. xxxi, 1936, pp. 253-262.

[2] Wedd, C. B. and W. B. R. King, 'The Geology of the Country around Flint, Hawarden, and Caergwrle', (*Mem. Geol. Surv.*), 1924, pp. 38-45.

[3] 'The Upper Keuper Sandstones of East Nottinghamshire,' *Geol. Mag.*, 1910, pp. 305, 306, 'Ball or Pillow-form Structures in Sandstones,' *Geol. Mag.*, 1916, pp. 146-156.

[4] 'Principles of Stratigraphy,' 1932, pp. 659, 780-784.

[5] 'On Subaqueous Slides,' *Geologiska Föreningens, Stockholm.* Förhandlinger, Band 53, Häft 4, pp. 377-393.

[6] Kendall, P. F., and H. E. Wroot, 'The Geology of Yorkshire,' 1924, pp. 153-160.

regarded as subaqueous gliding due to a special cause. Its effects, however, cannot be differentiated from those due to the other causes.

Lamplugh has attributed similar structures observed by him in Mesozoic and Tertiary rocks to "local stresses resulting in part from the differential contraction of sediments of diverse composition while losing their water of sedimentation, and in part from their unequal yielding under equal superincumbent load."[1] The same theme has been developed by Fearnsides (*op. cit.*, 1915-16, pp. 215-257), but with more particular reference to the formation of the shear-breccias he describes (*see* above, p. 114).

It may reasonably be inferred that in the present instance distortion began at the onset of loading under conditions of subaqueous gliding at the foot of the Haigh Moor Rock deltas, and that as loading increased, differential contraction continued to exert a deforming influence on the slowly compacting rocks. The process was aided throughout by the irregular subsidence of the area and by the unequal loading with superincumbent sediment.

So far, the distortion effects differ only in degree of intensity from those found commonly in interbedded sandstones and mudstones throughout the Coal Measures, and which may be regarded as due to a normal development of loading stresses. The localization of distortion at the base of the rock is due to the different contraction-rates of sand and mud (of the order of 1 to 6. *See* Fearnsides, *op. cit.*, 1915-16, p. 254). In the washouts, the severity of the plastic deformation, and the presence of sheared rock-breccias, points to a great concentration of pressure in those areas. It is probable that both the floor of the seam and the Haigh Moor Rock acted under pressure as rigid layers, between which the relatively yielding coal and roof-mud were squeezed. Accidental protuberances in the rock base, *i.e.* the solid fillings of the washout channels, transmitted the loading pressure as along line-contracts, and tended to squeeze out the weak strata on either side, thus inducing severe distortion and, as compaction increased, shearing and brecciation.

Final adjustment to pressure involved the general development of slickenside polish, followed, how soon afterwards is not known, by the incidence of cleat in the coal. The whole movement was evidently accomplished during sedimentation of the higher Coal Measures, of which at least 2,500 ft. remain in the area.

So far, the interleavings of sandstone (or mudstone) with coal have not been considered, for they present a problem which is not likely to be solved until more is known of the physics and mechanics of coal consolidation. They are not uncommon beneath rock roofs. They have been regarded by Jukes as cases of original

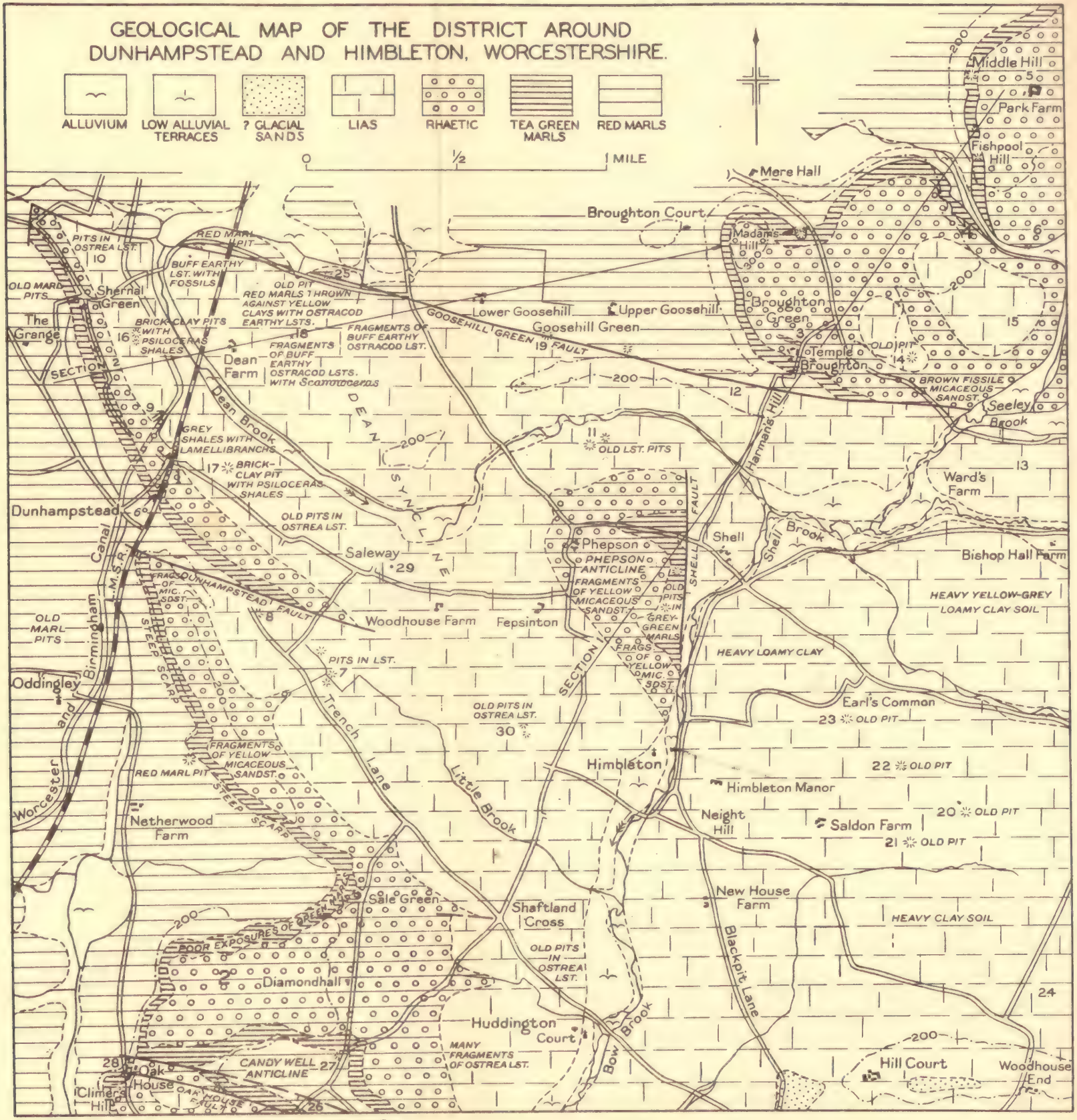
[1] 'On the Disturbance of Junction Beds from Differential Shrinkage and similar local Causes during Consolidation,' *Geol. Mag.*, vol. x, 1903, pp. 516, 517.

interbedding.[1] Fearnsides grouped them with the brecciation and other shear phenomena, while admitting that they presented inexplicable features (*op. cit.*, 1915-16, p. 597). Some features of the present examples suggest two other explanations : (a) the injection of quicksand (as inferred by Kendall, *op. cit.*, 1924, p. 159) into partly consolidated but already well laminated coal, or (b) deposition of sand in the interstices induced by the opening of the coal laminae on the edges of erosion channels, the effect of pressure-release attending the removal of the bind overburden.

Summary.—The washouts in the Haigh Moor Coal are an effect of stream-channelling accompanying the deposition of the Haigh Moor Rock, which lies close above the seam and fills the washout channels. There is some evidence to suggest a control of erosion by contemporary subsidence. The washouts are characterized by severe deformation of beds at and near the plane of erosion, due to the continuous application of loading stresses beginning with subaqueous gliding. The final adjustments of the heavily loaded sediments took place under conditions of shear, and were completed before the coal received its cleat.

Acknowledgments.—Thanks are due to Prof. W. G. Fearnsides for discussion and criticism of this paper, to Dr. D. A. Wray for details in the area south of Normanton, and to the directors, managers and surveyors of several West Yorkshire collieries, including especially New Sharlston, St. John's, Glass Houghton and Castleford, West Riding and Silkstone, Whitwood, Airedale Collieries, Ltd., and Ackton Hall, South Kirkby and Hemsworth Collieries Ltd., both for information supplied and for facilities to examine workings.

[1] Jukes, J. B., 'The South Staffordshire Coalfield,' ed. 2 (*Mem. Geol. Surv.*), 1859, pp. 45, 49-51, 202, 203.



NUMBERS REFER TO LOCALITIES MENTIONED IN THE TEXT.

IX. THE GEOLOGY OF THE DISTRICT AROUND DUNHAMPSTEAD AND HIMBLETON, WORCESTERSHIRE

BY

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Plate VII : Text-figures 1 and 2.

SOME four to eight miles east of the River Severn a broad tongue of Rhaetic and Liassic deposits extends northwards from the River Avon to Shernal Green, Broughton Green and Turret Hill, east of Droitwich. Bounded on the west, north and south by Keuper Marls, these rocks constitute part of the down-fold that, farther north, has been called the Droitwich Syncline.[1] Their western border presents in the main an unbroken escarpment overlooking the undulating plain of Keuper Red Marls, but the eastern margin is mostly faulted. The present paper deals with the north-western part of this tract. Given over almost wholly to agriculture and woodland, and of low relief, it is in places difficult to map, and the boundaries of the various beds are occasionally no more than conjectural. Nevertheless it has been possible to establish the existence of a number of minor folds within the major depression, and to prove the occurrence of the higher part of the Hettangian and possibly the lower part of the Sinemurian divisions of the Lower Lias.

I. Details of the Stratigraphy

Keuper

Red Marls.—Detailed description of these beds is unnecessary; they present essentially the same features here as over the greater part of the Midlands. A number of old marl pits show them as hard red or red-brown rocks, with cuboidal fracture. About 18 feet below their top occurs a thin grey or greenish-grey band, noticeably harder than the associated red layers; this is well displayed in the pits north-east of Netherwood Farm and north-west of Shernal Green (Plate VII).

Tea Green Marls.—These white, grey and greenish marls, appreciably harder than the Red Marls, are also similar to their equivalents elsewhere. At their base, red and grey bands alternate for a thickness of a foot or two, but otherwise the transition is

[1] 'Summary of Progress for 1931' (*Mem. Geol. Surv.*), Part II, 1932, p. 44.

rapid—almost abrupt—and easily mapped. The Marls are frequently exposed in, and form the major element of, the western escarpment, which is largely due to their relative hardness supplemented by that of the overlying Rhaetic sandstones. Partial sections occur in some old pits, not yet completely overgrown, on the slopes of Fishpool Hill, Middle Hill, and, farther north, of Forest Hill. The sequence seen in the railway cutting at Dunhampstead[1] is complete, and it is nearly so in the roadside at Temple Broughton Farm, and in an old pit south-east of Mere Hall. The thickness at Dunhampstead may be accurately measured as 34 ft.[2] Elsewhere such accuracy is not attainable, but at Climer's Hill, the Marls are given by Richardson[3] as about 31 ft. thick. On the other side of the Goosehill Green Fault, however, near Temple Broughton, they are certainly less than 30 ft.—probably not much more than 20 ft.—and they appear also to be relatively thin near Mere Hall, on Fishpool Hill, and on Forest Hill.[4] It would seem, then, that changes in thickness, observed in other parts of the country, take place in this area within relatively short distances: hence, if the grey colour of the Marls is original, a considerable non-sequence at the base of the overlying Rhaetic is strongly implied.

Rhaetic

As the classic exposures at Dunhampstead and Climer's Hill have unfortunately become much overgrown, while no new sections have been cut, Harrison's detailed account and Richardson's more recent regional study, both already cited, have largely to be drawn upon for the following details of these rocks.

At Dunhampstead the downward succession is as follows:—[5]

		Thickness Ft.	In.
4	Sandy shales and clays	5	0
5a? } 5b }	Hard grey-black shelly limestone, weathering with rusty spots and blotches. Fossils include *Chlamys* [*Pecten*] *valoniensis* (Defrance), *Pteria* [*Avicula*] *contorta* (Portlock), *'Cardium' cloacinum* Quenstedt, *Pleurophorus sp.*, *Gervillia sp.*, *'Axinus' sp.* (probably *'Schizodus' ewaldi* (Bornemann)), and fish remains. According to Richardson this is the equivalent of the Upper Pecten Bed of other places	0	1

[1] *See* W. J. Harrison, 'On the Rhaetic Section at Dunhampstead Cutting, Droitwich, and its Connection with the Same Strata Elsewhere,' *Proc. Dudley & Midland Geol. & Sci. Soc.*, vol. iii, 1877, plate.

[2] The thickness is given as 35 feet by Harrison, *op. cit.*, p. 121 and (presumably after Harrison) by L. Richardson, 'Observations on the Rhaetic Rocks of Worcestershire,' *Trans. Worcs. Nat. Club*, vol. iii, 1904, p. 97.

[3] Richardson, L., 'The Rhaetic Rocks of Worcestershire,' *Proc. Cotteswold Nat. Field Club*, vol. xv, 1904, p. 26.

[4] 'Summary of Progress for 1931' (*Mem. Geol. Surv.*), *loc. cit.*

[5] The numbering of the beds follows the practice adopted by Richardson in his discussions of the Rhaetic rocks of this country. Harrison numbered his beds differently, and in reverse order, but his account is easily collated with Richardson's.

		Thickness Ft.	In.
6	Brown shales	2	0
7	Limestone nodules, wrapped in shales, reaching	0	10
8	Black pyritous argillaceous shales	2	7
9, 10, 11	Brown micaceous sandstone with *Volsella sp.* and '*Schizodus*' *sp.*	0	3
12	Brown argillaceous shales	1	2
13	Yellow micaceous sandstone, weathering brown. Fossils include *Volsella* [*Modiola*] *minima* (J. Sowerby), '*Schizodus*' *sp.*, annelid tracks, and fish scales	0	5
14	Brown and black 'paper shales'; *Pteria contorta* with *Protocardium rhaeticum* (Merian), and '*Schizodus*' *sp.*	0	2
15	White or yellow highly fissile micaceous sandstone, weathering to a rusty brown. It is of variable thickness, and in places its surface is ripple-marked. Many specimens of '*Schizodus*'	c.2	1
16	Black and brown shales, sometimes argillaceous, thinly laminated, with '*Schizodus*' *ewaldi*? and *Pteria contorta* ...	3	0
17	Hard micaceous yellow sandstone, rippled-marked and with oblique lamination. At the base occur a few inches of shales. Fossils include annelid tracks and abundant specimens of '*Schizodus*' *ewaldi*	1	1
		20	6

In the quarry immediately west of Oak House, near Climer's Hill, Crowle (**28**),[1] the succession, recorded by Richardson, is closely similar to that at Dunhampstead. The upper beds (4 to 7) are not present. In the others, the only notable difference is an increase of Bed 13 from 5 in. to 9 in., presumably by an encroachment of the sandstone facies upon the shales beneath, which are correspondingly reduced. Bed 13 carries an additional fossil, *Gyrolepis*. It should be further noted that Bed 15 is only about half as thick as at Dunhampstead.

Regarding Bed 15 as equivalent to the " true " Bone Bed of Aust and Sedbury on Severn, Richardson[2] has attributed the absence of Bed 17 at other localities in Worcestershire to a sub-Rhaetic non-sequence, due, in his opinion, to regional flexuring. Local circumstances of deposition may perhaps be a more likely cause of the non-sequence, for similar sandstones at a higher horizon thin away or die out within short distances (*e.g.*, Bed 15 between Dunhampstead and Climer's Hill).

No higher beds than the above were recorded by Harrison, or by Richardson, who referred them to the Lower Rhaetic. The recent erection of telegraph poles along the railway at Dunhampstead, north of the bridge, has displayed about 10 feet of light-grey and greenish-grey poorly stratified soft greasy clays, not far below the lowest beds of the Lower Lias. These are the equivalents of

[1] The figures in heavy type refer to the correspondingly numbered localities on the map.
[2] Richardson, L., 'The Evidence for a Non-Sequence between the Keuper and the Rhaetic Series in North-West Gloucestershire and Worcestershire,' *Quart. Journ. Geol. Soc.*, vol. lx, 1904, p. 349.

the Upper Rhaetic shales described by Richardson[1] as occurring at Woodnorton, near Evesham, where they are poorly fossiliferous; here they contain abundant specimens of *' Schizodus ' ewaldi* and *Protocardium rhaeticum*, and their full thickness is estimated to be about 15 to 18 ft. Their outcrop is marked by a depression at the foot of the Rhaetic dip-slope.

Poor exposures of Lower Rhaetic sandstones are seen at various places near the main escarpment. In the fields west of Diamond-hall (**2**) they make the floor of the long dip-slope; fragments brought up by the plough have yielded many scales of *Gyrolepis*, teeth of *Saurichthys*, and internal moulds of lamellibranchs. Immediately south of the Dunhampstead Fault, shallow excavations in a ditch yielded beautiful examples of a bone-bed with abundant fish remains, including *Gyrolepis, Saurichthys, Acrodus* and *Sargodon*, in a highly micaceous white and yellow fissile sandstone; this rock is almost certainly Bed 15. At Temple Broughton Farm (**3**), the junction with the Tea Green Marls shows a fissile micaceous sandstone—almost certainly Bed 17—about 14 in. thick, with many moulds of lamellibranchs and with fish remains, including *Gyrolepis* and *Nemacanthus*. In the lane 450 yds. north-north-west of Ward's Farm, a rust-brown micaceous sandstone contains abundant moulds of *Schizodus* ? and *Pleurophorus* ?

South-west of Park Farm, a yellow fissile micaceous sandstone exposed in a small pit (**4**) seems to be Bed 15, and has yielded well preserved moulds of *' Schizodus ' ewaldi, Mytilus cloacinus* Tutcher and *Pleurophorus elongatus* Moore. Similar fossils are found in fragments brought up by the plough in the fields west and north-west of Park Farm (**5**).

A single loose fragment of shelly limestone with rusty blotches, found on Fishpool Hill (**6**), is almost certainly the equivalent of Bed 5b; it contains abundant specimens of *Chlamys valoniensis* and *' Schizodus ' ewaldi*.

These Rhaetic sandstones, all very similar in thin section, are completely decalcified highly micaceous rocks composed mainly of sub-angular grains of quartz of an average diameter rather less than 0.5 mm., often coated with a thin ferruginous film; scattered grains of a dark brown mineral appear to be limonite. A large number of the quartz grains are acutely angular, and would seem to have travelled no great distance.

Lias

Only the lowest, essentially argillaceous, beds of the Lower Lias are known to occur in this district. The typical lithology of the ' Blue Lias ' is seen only in the lowest few feet. Exposures are relatively few and poor, though formerly a number of lime pits were worked, particularly in the Ostrea Beds. Nevertheless, the

[1] Richardson, L., *Proc. Cotteswold Nat. Field Club, op. cit.*, p. 38.

following broad succession can be made out, the thicknesses given having been estimated[1] from widths of outcrop within the area included in the map:—

iii. Shales and clays with buff and yellow muddy limestones. These include the Angulatum Zone (Upper Hettangian) and possibly part of the succeeding Bucklandi Zone (Lower Sinemurian). Thickness, not less than 80 to 100 ft.

ii. Black and brown laminated shales with thin bands of nodular limestones. The Psiloceras Shales. Thickness, 25 to 30 ft.

i. A series of alternating grey shales and highly fossiliferous grey limestones. The Pre-Planorbis or Ostrea Beds. Thickness, 15 to 20 ft.

These divisions, by their different effects on topographical features, are useful in mapping, but are essentially lithological. In particular, no precise limitation of the Psiloceras Shales to the Planorbis Zone is intended, even in its broad interpretation; their upper part may well belong to the Angulatum Zone (*sensu lato*). Evidence from ammonites is rare, and has had to be supplemented by that of the lamellibranchs.

Ostrea Beds.—These are now only poorly exposed in partly overgrown quarries, abandoned several years ago. They were first described by Roberts.[2] Richardson's section of a quarry at Saleway (**29**)[3] was obtained at a time when the beds were actually being worked:—

		Thickness Ft.	In.
	Blue and yellowish marl with patches of red sand and a few 'Northern Drift' pebbles	7	0
Lower Lias (*Pre-Planorbis*)			
1	Blue and yellowish marl	2	0
2	Limestone, hard blue; *Ostrea liassica*	0	3
3	Parting of brown shales	0	0½
4	Hard blue limestone with *Ostrea liassica*	0	5
5	Parting of brown shales	0	1
6	Hard blue limestone	0	2
7	Parting of brown shales	0	0¼
8	Hard blue limestone	0	2
9	Parting of brown shales	0	0¼
10	Hard blue limestone with saurian remains; variable, about	0	6
11	Marly shales with saurian remains and a coral	0	5
12	Hard blue limestone, the 'brick bed'	0	3
13	Greyish-blue argillaceous limestone, fissile in places, crowded with *Ostrea liassica* and *Volsella minima*; the 'bottom bed'	0	2
14	'Clay'	0	8
15	'Limestone'	0	4
16	'Clay'	2	0
Upper Rhaetic			
1	'Limestone', the Pseudomonotis Bed?	0	4

[1] Some difficulty is introduced into mapping and the estimation of thicknesses by the one-time practice of excavating fields to a depth of as much as 3 or 4 ft., to remove the harder limestone bands that interfere with ploughing, the surface soil and shales being replaced for tillage. Such 'brent' ground is especially common on the outcrop of the Ostrea Beds.

[2] Roberts, G. E., 'The Rocks of Worcestershire,' 1860, p. 204.

[3] Richardson, L., *Proc. Cotteswold Nat. Field Club, op. cit.*, p. 33. Mr. Richardson has kindly pointed out the exact site of this and the Himbleton quarry, described by him.

The beds are evidently much the same in a quarry[1] at Himbleton (**30**) as in other parts of the country. They are Pre-Planorbis in age; no ammonites were found in them during the present survey.

The old pits just north of Huddington, and those at Saleway, are completely overgrown, but *Ostrea liassica* is abundant in limestone fragments scattered over the fields west of Huddington Court, and occurs with *Volsella minima* and cidaroid fragments in two of the pits (**7**, **8**) north-east of Trench Lane. In the canal and railway cuttings at Dunhampstead (**9**, **1**) a rib of Ostrea limestone is found within a foot or two of the Rhaetic shales. *Ostrea liassica* and *Volsella minima* are abundant in this and also in limestone fragments from old pits near Shernal Green (**10**) and from a pit on the canal bank 400 yards south-west of Dean Farm. At the last mentioned locality *Pleuromya tatei* Richardson and Tutcher occurs in addition.

A considerable distance to east of the above, the same three species are common in scattered limestone fragments west of Harman's Hill (**12**). Similar fragments occur around some overgrown pits north of Phepson (**11**), and the limestone is in place in old workings westward from Himbleton. The fragments at locality **13** contain *Volsella laevis* and *Pleuromya sp.*, in addition to abundant specimens of *Ostrea liassica, Volsella minima,* and cidaroid plates and spines. The two outliers (**14**, **15**) north of the Goosehill Green Fault yield a similar fauna : *Ostrea liassica, O.* cf. *irregularis, Pleuromya sp., Cardinia ovalis* Stutchbury, and cidaroid remains occur in limestone fragments from the old pit at **14**.

Psiloceras Shales.—These are blue, grey and brownish shales with thin bands of nodular muddy limestone; there is probably a gradual lithological passage upwards from the Ostrea Beds, but nowhere has the junction been seen. As the proportion of argillaceous material is much greater than in the Ostrea Beds, these Shales tend to occupy much of the dip-slope behind the small scarp of the Ostrea Beds, and the hollow at the foot of the slope.

Exposures are confined to a small tract near Shernal Green and Dunhampstead. In two pits (**16**) where the Shales have been worked for brick clay, they contain numerous crushed specimens of *Psiloceras planorbis* Sowerby, preserved as films on the bedding planes in the manner usual in these sediments. In an old clay pit to the south-east (**17**) the Shales contain two thin bands of buff muddy limestone, 15 in. apart, which yield *Volsella minima, Lima hettangiensis* Terquem and *Cardinia sp.*, in addition to *Psiloceras planorbis,* which is also abundant in the shales.

Upper Hettangian Beds.—These also consist of shales and clays with muddy limestones. No detailed succession has been seen, but a low distinct scarp-feature suggests that the limestones

[1] Richardson, L., 'The Lias of Worcestershire,' *Trans. Worcs. Nat. Club*, vol. iii, 1905, p. 198.

occur in particular force only a short distance above the Psiloceras Shales.

The limestone blocks thrown out at locality **18** have yielded fragments of a schlotheimiid ammonite similar in the details of its costae and whorl shape to *Scamnoceras acuticostum* Strickland-Buckman[1] together with numerous specimens of *Volsella hillanoides* Chapuis and Dewalque[2] and *Ostrea* cf. *irregularis,* crinoid columnals, and ostracods (? *Cytheridea sp.*); ostracods also occur in similar limestones in old pits west-south-west of Goosehill Green.

Two pits near here (**19, 25**) show Red Marls brought by the Goosehill Green Fault into contact with Lias clays that probably belong to the Angulatum Zone and at **19** contain *Cardinia listeri* and gastropods.

East of the Bow Brook exposures are rare and few ammonites have been found. Fragments of a brown earthy crinoidal limestone at locality **20** carry impressions of what appears to be a caloceratid or alsatitid ammonite, associated with *Lima gigantea* J. Sowerby and *Cardinia*. An angulatid ammonite has also been found at locality **21**. Elsewhere the Angulatum Zone is indicated by the lamellibranch fauna; for instance, at locality **22**, where *Ostrea* cf. *irregularis, Volsella hillanoides, V.* cf. *liasana* (Terquem)[3] and *Lima gigantea* were found, and at **23**, which yielded a similar fauna, with *Volsella hillanoides*.

Lower Sinemurian Beds.—These may be represented in the extreme south-east of the area (**24**). A single specimen of *Gryphaea* aff. *obliquata* Sowerby, found on the surface of a ploughed field, possibly indicates the lower part of the Bucklandi Zone; almost certainly it cannot have been derived from a horizon much below the upper part of the Angulatum Zone.

II. Structure

That the area is part of the western limb of the Droitwich Syncline, is indicated by the general trend of the escarpment outcrop of Tea Green Marls and Rhaetic rocks; but dips are rarely seen, and are invariably low, the angle of about 6° north-east, found in the railway- and canal-cuttings at Dunhampstead, being the steepest observed. The inclination is usually insignificant in small exposures, but may, in places, be shown by the dip-slopes; for example, it is about 1 in 45 to east, near Sale Green, and about 1 in 25 to south-east, near Broughton Green.

[1] *Scamnoceras acuticostum* has been recorded from Ennick Ford, little more than a mile south of Hill Court; *see* L. Richardson, *op. cit.*, 1905, p. 199; S. S. Buckman, 'Some Lias Ammonities; *Schlotheimia* and Species of Other Genera,' *Proc. Cotteswold Nat. Field Club*, vol. xv, 1906, p. 236.

[2] This species is characteristic of the Angulatum Zone; *see* L. Richardson and J. W. Tutcher, 'On *Pteromya crowcombeia* Moore and Some Species of *Pleuromya* and *Volsella* from the Rhaetic and Lower Lias,' *Proc. Yorks. Geol. Soc.*, vol. xix, 1916, p. 54.

[3] This species also appears to be characteristic of the Angulatum Zone; see *ibid.*, p. 55.

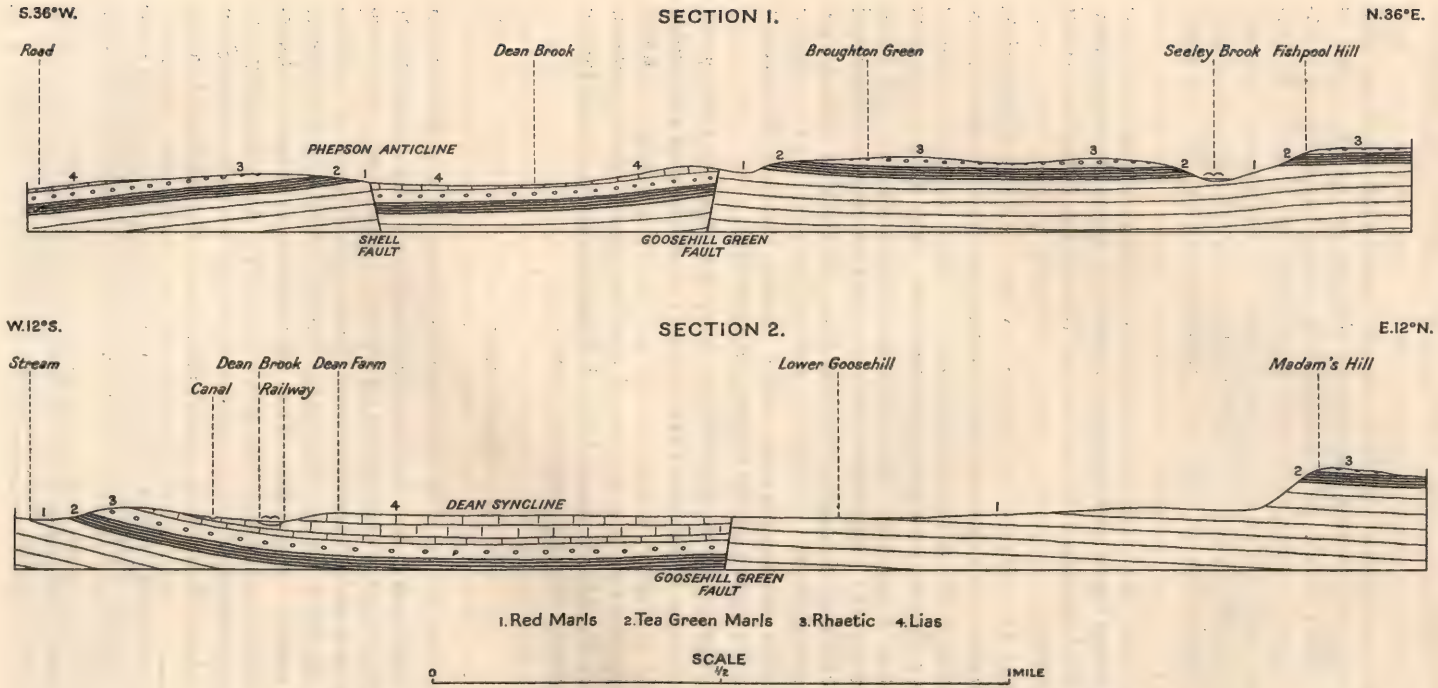

FIG. 1.—*Section from near Himbleton to Fishpool Hill. Horizontal scale 3 inches to 1 mile; vertical scale three times horizontal.*

FIG. 2.—*Section from near Dunhampstead to Madam's Hill. Horizontal scale 3 inches to 1 mile; vertical scale three times horizontal.*

Within this major limb, however, may be recognized a number of minor structures, both faults and folds.

Faults.—The most important fault, here called the *Goosehill Green Fault,* was indicated by De La Beche on the Survey map as long ago as 1854. Most of its course is easily traced, by means of the contrast between reddish and brown clay soils from the red Keuper Marls, with the grey and yellow clays of the Lias country. The position is exactly fixed in two old pits already mentioned (**25** and **19**). East of Harman's Hill the fault is difficult to follow, but would seem to run along the floor of the Seeley Brook. The throw is very variable and near Lower Goosehill, where Keuper Red Marls are in contact with the Angulatum Zone, it cannot be less than about 130 ft., even if the Marls are the highest beds of the group. Much more probably, they are at a lower horizon, the dip determined on Madam's Hill continuing appreciably unaltered up to the fault (Fig. 2); the throw then approaches 280 ft. South of Broughton Green (Fig. 1), the throw is less certainly calculated to be not much more than about 80 ft.; while still farther east the Ostrea Beds near Ward's Farm are at most a few feet below those on the north side of the fault. Westward from Lower Goosehill, the evidence is inconclusive, as no dips are seen in the Red Marls, but the fault is not traceable much beyond Shernal Green, and may die out in that direction. This would make it essentially a ' sag ' fault, the beds on the south side having sagged into a shallow downfold (the Dean Syncline), while the beds on the north, though given a general easterly tilt, remained relatively rigid.

Farther south, the minor Dunhampstead and Oak House Faults, with the same trend, and the same southerly downthrow, are presumably of much the same age and origin.

The *Dunhampstead Fault,* very clearly displayed in the railway cutting,[1] may be followed to an old pit in Trench Lane, where Red Marls are seen against yellow clays. It too dies out eastwards, and cannot be recognized around Himbleton. In the railway-cutting the southerly downthrow is about 70 to 80 ft.,[2] but it cannot be much over 20 or 25 ft. in the ground between Woodhouse Farm and Trench Lane, where only Ostrea Beds seem to be exposed at the surface, unless a small shallow outlier of Psiloceras Shales is present a few hundred yards south of Woodhouse Farm.

The faults near Oak House are very small,[3] though the southern (the ' *Oak House Fault* ' of Plate VII) has the effect of preserving a small outlier of Ostrea Beds.

The *Shell Fault,* running north and south, nearly at right angles to the other fractures, can be traced with considerable

[1] *See* W. J. Harrison, *op. cit.*, plate.
[2] Harrison's estimate (*ibid.*, p. 120) ' over 100 feet ' is considerably too much.
[3] According to L. Richardson (*Proc. Cotteswold Nat. Field Club, op. cit.*, p. 25) the southern fault has a throw of about 14 feet.

accuracy by the contrasting natures of the soil on its two sides. The outcrops mapped on the western side of the fault can also be determined with some degree of precision. The horizon of the Liassic rocks on the eastern side is uncertain. As an old lime pit occurs 300 yards north of Shell Manor, they are shown in Fig. 1 as belonging to the Ostrea Beds, which means a throw near Shell of at least some 80 to 100 ft.; if the Liassic rocks are younger, the throw is more. Traced northwards, however, the fault dies away; Ostrea Beds are seen on both sides of it at **11** and **12**, and it seems not to affect the Goosehill Green Fault.

The closing of the outcrops mapped on the western side of the fault strongly suggests a dying out southwards also; definite evidence is lacking near Himbleton, but the apparently unbroken succession between Huddington Court and Hill Court seems to show that there is no fault in that neighbourhood. It may then be reasonably concluded that the Shell Fault is yet another fault with variable throw, the strata of the western side being arched relatively to those of the eastern.

Folds.—The great rarity of undisturbed exposures precludes determination of flexures by dip observations—indeed no westerly dips have been seen—and the evidence of folding is entirely based on the distribution and topographical relations of outcrops.

The Dean Syncline (Fig. 2) in which lies the small outlier of the Angulatum Zone about **18**, is the most important structure in the area. Its general form is fairly clearly delineated by the Dean Brook between Shernal Green and Shell. North of the area shown on the map this stream flows for a mile in a south-westerly direction over featureless Red Marl country, but on crossing the Goosehill Green Fault its course is progressively diverted, first south, then eastwards, subsequently swinging from north-east to south-east around Phepson. This course over the Lias is almost perfectly adapted to the geological structure: the brook has become a strike stream following the hollow (p. 124) at the foot of the dip-slope of Ostrea Beds. Its left bank is a steep scarp, chiefly of Upper Hettangian beds, that rises in places 50 and 60 ft. above the alluvium. The Ostrea Beds that, locally with a thin cover of basal Psiloceras Shales, floor the right bank can be traced by old limestone pits from Shernal Green to an area north of Phepson, beyond which the stream transgresses the outcrops and crosses the Shell Fault. The Dean Syncline is thus essentially a basin with a slight northerly pitch, truncated by the Goosehill Green Fault. South of the Dean Brook, the fold trends south-eastwards with a flattening of pitch between the Rhaetic beds of the main scarp and the same beds north of Himbleton. It is probably somewhat asymmetrical, the Little Brook occupying its core. Beyond the Bow Brook it apparently dies out, for the ridge running south from Neight Hill along Blackpit Lane seems to be the scarp of the Upper Hettangian Beds.

The structure complementary to the Dean Syncline is the

Phepson Anticline. The Rhaetic and Keuper rocks brought to the surface by this upfold (Fig. 1) cover only some 100 acres of the higher ground about Phepson. Their precise limits are indefinite, but fragments of Rhaetic sandstone are common in fields south and south-east of Phepson, while Tea Green Marls are exposed in old pits south-west of Shell. A tiny inlier of Red Marls is present where dark red clays have been thrown out of a ditch along the road leading westwards from Shell. The anticline closes towards the north-west, and seems to be bounded on the east by the Shell Fault. Paucity of exposures prevents its being recognized near Earl's Common, if it is continued across the fault.

The Candy Well Anticline, a gentle faulted fold between Climer's Hill and Huddington, is clearly outlined by an escarpment of the Tea Green Marls fairly readily traceable from a point north of Oak House to the road junction south of Diamondhall, where it swings southwards. The outcrops on the faulted southern flanks of the fold are somewhat indefinite, but the outlier of Ostrea Beds, and a pit in Tea Green Marls at **26** indicate their general trend. A depression now marks the core of the anticline occupied by Red Marls, whose presence is indicated by the reddish soil and in the pit at **27**. A small stream that flows more or less along the axis, and is partly tapped at Candy Well (just off the map), has its gathering ground on the flanks of the anticline, where the surface run-off is probably supplemented by ground-water thrown out at the base of the Rhaetic sandstones. The well, too, lies on the line of the northern Oak House Fault. These considerations suggest a somewhat different view from that of Richardson[1] on the Candy Well, and may in part explain why its water is of better quality than that usually obtained from the Lias.

[1] Richardson, L., 'Wells and Springs of Worcestershire', (*Mem. Geol. Surv.*), 1930, p. 48

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